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VOLUME I

A FUEL TANK INERTING SYSTEM FOR MILITARY AIRCRAFT

JOHN L. WARNER, H. JAEGER
HAMILTON STANDARD DIVISION OF UNITED AIRCRAFT CORPORATION

TECHNICAL REPORT AFAPL-TR-70-85 VOLUME I

FEBRUARY 1971

AIR FORCE AERO PROPULSION LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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AFAPL-TR-70-85-Vol I.

A FUEL TANK INERTING SYSTEM FOR MILITARY AIRCRAFT

VOLUME I

Hamilton Standard
Division of United Aircraft Corporation

TECHNICAL REPORT AFAPL-TR-70-85, VOLUME I

FEBRUARY 1971

AIR FORCE AERO PROPULSION LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FOREWORD

This is the final report, consisting of Volumes I and II, on a Fuel Tank Inerting System for Military Aircraft Contract F33615-70-C-1616. The work was performed for the Air Force Aero Propulsion Laboratory by the Hamilton Standard Division of United Aircraft Corporation, Windsor Locks, Connecticut under Project 8048, Task 304807. This effort was funded with FY70 Air Force Aero Propulsion Laboratory Director's Funds.

The Air Force Project Engineer is Mr. Steven D. Shook (AFAPL/SFH) who directed the program for the Support Technology Division, Air Force Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio.

At Hamilton Standard, Mr. J. L. Warner directed the Program assisted by Mr. H. Jaeger.

This report required the support of The American Cyanamid Corporation, for the catalytic reactors under Hamilton Standard Contract No. E862581 NL.

The report was submitted in February 1971 and covers work performed from May through October 1970. The Hamilton Standard designation for this report is HSER 5764.

This report has been reviewed and is approved.

Benito P. Botteri

Benito P. Botteri
Chief, Fire Protection Branch
Fuels and Lubrications Division

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ABSTRACT

Fuel tank inerting requirements for two typical military aircraft have been established. With these requirements as a basis various inerting systems using a catalytic combustor have been considered and an optimum configuration has been selected for further study. A preliminary design has been completed on this configuration, including weights, general configuration, control functions and performance. The weight of the system is approximately 50% of a liquid nitrogen system designed to meet the same requirements. The moisture added to the fuel tanks is approximately the same as that added to the current fuel systems which do not have inerting systems. A program plan for the follow-on program which consists of building and testing a breadboard system of this configuration has been prepared.

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1.0 INTRODUCTION

Fire and explosion hazards in aircraft fuel tanks arise from the presence of a combustible mixture of fuel vapor and oxygen in the space above the fuel. Oxygen comes out of solution in the fuel, and air may enter at unprotected vents. The mixture may be combustible over a wide range of frequently encountered temperatures. Penetration of projectiles, ignition at the tank vent by lightning and local heating by lightning or by fire can result in fuel tank and venting system explosions and fires. Fuel tank inerting systems have been used successfully in which a stored inert gas such as nitrogen is supplied to the interior of the tank, purging it of oxygen to noncombustible levels.

The present study has been undertaken to develop a preliminary design of a system for producing an inert gas from air by burning fuel to reduce its oxygen content. The approach taken is to perform the burning on a catalyst bed supplied with engine bleed air and fuel. Heat is rejected to ram air and moisture is condensed in an air cycle refrigeration unit.

The study comprises four major tasks aimed at developing a preliminary design of the catalytic reactor inerting concept. The first involves writing specifications for the inerting systems to cover the requirements of two aircraft, the Tactical Fighter Aircraft (TFA) and the B-1. The second task covers concepts for catalytic reactor inerting systems for the two aircraft. One concept, that for the B-1, is developed into a preliminary design in the third task. Finally, the fourth task describes a breadboard development program for ground testing of a catalytic reactor type fuel tank inerting system. A concept has been developed in the study that makes use of a catalyst in the form of packed beds of pellets that promote the reaction between fuel and air at about 1300°F. Combustion heat is transported by a large volume of recirculating gas to the heat exchangers which reject it to ram air. The inert gas, still at close to bleed air pressure, is further cooled in heat exchangers and is expanded in a turbine, bringing temperatures close to freezing for maximum condensation and drying. Moisture is discharged into the ram air inlet for its cooling benefit and the dry, inert gas is delivered to the aircraft fuel tank.

2.0 DEFINITION OF SYSTEM REQUIREMENTS

As Task I of the study program reported herein, the Fuel Tank Inerting System requirements were established for a Long Range Bomber (B-1) and a Tactical Fighter Aircraft (TFA). A system specification was prepared for each aircraft, including an outline of the general system requirements and detailed flight profiles for two typical missions, one subsonic and one supersonic. The full details of the flight profiles are classified secret and are available only through limited distribution. The general system requirements, which are essentially alike for both aircraft are presented below, followed by a discussion of specific B-1 and TFA requirements.

It is to be noted in reviewing this presentation of the system requirements that they represent a composite of information gathered from several sources over a time span of considerable length relative to the overall study duration. The flight profile data, in particular, was based on inputs from both the Air Force and the airframe prime contractors and, simply due to the early stages of development of both aircraft, contain many approximations.

General Requirements

Fuel Tank Oxygen Level

The requirement for the fuel tank inerting system is that the oxygen concentration in the fuel tank vapor space be maintained at a level below that which will support combustion. A concentration of 9% by volume was established as the maximum allowable. This is to be accomplished by means of reducing the oxygen level of engine bleed air in a catalytic combustor and feeding the inert gas to the fuel tank.

Moisture Removal

The inerting system design objective is to provide moisture removal capacity to the extent that the moisture added to the fuel tanks over the specified flight profiles would not exceed that added by the atmosphere to unprotected tanks. This design objective led to the establishment of a maximum absolute humidity of 80 grains water/lb dry gas delivered to the fuel tanks under all normal operating conditions.

Fuel Tank Pressure Control

The inerting system is required to control the flow of inerting gases to the fuel tanks in such a manner that a specified pressurization schedule is maintained. The normal fuel tank pressurization is 0.5 psig or 6.0 psia, whichever is greater. The fuel tank pressure relief valve will prevent overpressurization and the drive valve will not allow negative pressure in the tanks.

Fuel Compatibility

The inerting system is to be compatible with JP-4, JP-5, and JP-8 fuels while meeting the requirements of the specification. In addition, no hazard shall be added by the inerting system while the aircraft is operating on emergency fuel consisting of 97% aviation gasoline and 3% lubricating oil.

Heat Sink Availability

Both ram air and fuel are available as heat sinks to meet the cooling demands of the system. A design objective is to minimize the use of fuel as a heat sink.

Operating Requirements

The operating modes of the inerting system are described by specifying what is required of the system during various phases of a typical aircraft operation cycle.

Climb

During climb the quantity of dissolved oxygen and nitrogen which the fuel can hold in equilibrium is reduced. These gases, dissolved in the fuel during ground storage, tend to stay in solution in a supersaturated condition as the pressure is reduced unless the fuel is agitated. To prevent the oxygen from coming out of solution when sporadic agitation occurs and disturbing the safe oxygen concentration in the tank ullage a fuel scrubbing process is required. Scrubbing will be accomplished by injecting the inerting gas into the liquid fuel to promote agitation and maintain equilibrium of the dissolved gases in the fuel during climb. The injected inerting gas will serve to dilute the oxygen to a safe concentration in the ullage. A continuous venting

of inerting and emerging gases is provided by the tank pressure relief valve. The minimum volume flow rate of inerting gas required for adequate sparging during climb has been assumed to be equal to the volume flow rate of the fuel consumption at sea level. If a higher flow rate is necessary it can be provided without increasing the system size. The mass flow rate of inerting gas should remain essentially constant with increasing altitude until the tank pressure becomes constant.

Cruise and Descent

During cruise and descent the inerting system is required to maintain fuel tanks at the specified pressurization by controlling the flow of inerting gas into the tanks.

Fueling

During fueling on the ground and in flight the entering fuel can be supersaturated with air. Oxygen emerging from solution could enrich the ullage space far in excess of the safe limit. The inerting gas supply should be capable of scrubbing the fuel and purging ullage space to maintain a safe concentration in the ullage.

Ground Operation

It is desireable to provide inerting protection on the ground during stand-by. Over extended periods, with engines off, operation of the inerting system would be possible by making periodic use of hot, compressed air from an APU.

Emergency Operation

In the event of emergency descent rates a safe oxygen concentration and positive tank pressurization are to be maintained.

Logistics and Maintenance Requirement

System regeneration, maintenance and overall life is required to be consistent with the intent of the Bare Base Concept. The inerting system should be capable of multi-mission operation without external regeneration, replacement, or maintenance. The number of mission cycles between such maintenance will not exceed six.

TFA System Requirements

The normal maximum flow rate required for the TFA to maintain positive pressure in the fuel tanks is approximately 4.5 lb/min. This flow demand occurs with the aircraft approaching sea level in descent at the maximum normal descent rate with the fuel tanks nearly empty. In the event of an emergency descent, which, for the TFA, was specified as occurring during normal combat maneuvers, the descent rate is approximately six times the maximum normal rate. These combat maneuvers are assumed to occur between 25,000 ft and 10,000 ft altitude.

B-1 System Requirements

The normal maximum flow rate required for the B-1 to maintain positive pressure in the fuel tanks is approximately 75 lb/min. This flow demand occurs with the aircraft approaching a 3,000 ft loiter altitude in descent at the maximum normal descent rate with the fuel tanks near empty. In the event of an emergency descent, the flow demand for maintenance of positive fuel tank pressure to 3,000 ft may reach 200 lb/min.

The normal descent condition occurs with the engines at idle power setting. The emergency condition has sufficient engine throttle advance so as to assure adequate bleed flow availability. These flight conditions are the design points for the system. Specifically the system was designed to provide the normal maximum flow of 75 lb/min of inert gas at 3,000 ft hot day, M=0.025 and engine idle pressure. Collectively these conditions represent the severest operating condition and each has a direct influence on the resultant system size. A system sized to provide that amount of inert gas during normal maximum descent will also meet the emergency descent requirement when supplemented with engine bleed.

3.0 SYSTEM CONCEPT SELECTION

3.1 Concept Philosophy

There has long been a recognition of hazards associated with the mixture of fuel vapors and air in the space above the fuel in aircraft fuel tanks. Over the past 30 years various schemes have been tried for reducing or eliminating these hazards, usually by purging the ullage space of oxygen. Inerting with combustion products has been applied in the past using reciprocating engine exhaust products, and also using combustion products produced by purge gas generators designed from heater technology. The latter were never evaluated by flight test, and that technology is now fifteen years old. At the present time fuel tank inerting has become a recognized need for military aircraft as protection against enemy action. During 1968 and 1969 United Aircraft Research Laboratories conducted studies on various types of gaseous inerting systems with emphasis on combustion. Concurrently, American Cyanamid, under Air Force contract, was experimentally and analytically investigating a catalytic reactor type of combustion inerting system. From these programs it was evident that a combustion system based on the use of engine bleed air to react with aircraft fuel, and the use of ram air as a primary heat sink, offered significant advantages over other systems. These advantages appeared most prominently in weight savings and in the reduction of logistics support requirements.

The scope of this study was to apply the American Cyanamid catalytic reactor results to a system based on the use of aircraft equipment design principles for heat exchangers and controls. The system was also to make use of aircraft air-cycle refrigeration equipment for the removal of moisture produced in the combustion reaction. Full advantage was to be taken of the great affinity of SO_2 gas for moisture in the removal of this potentially corrosive combustion product from the inerting gas. Automatic controls to maintain stable operation at all conditions requiring inert gas production within the aircraft flight profile were included in these requirements.

A possible alternate to this system concept includes the use of a jet engine type burner and a single high temperature heat exchanger as a substitute for the catalytic reactor and its cooling heat exchangers. All other parts of the system would remain essentially unchanged. The burner would thereby permit avoidance of some of the reactor control problems while simplifying the system. Such a system was not considered in

detail since it was beyond the scope of the current program.

3.2 Catalytic Reactor Design

In a prior program sponsored by the Air Force Aero Propulsion Laboratory, American Cyanamid Company explored the feasibility of utilizing a catalytic combustion technique to provide inert ballast gas for the ullage spaces in aircraft fuel tanks. To a large extent the earlier work comprised a catalyst screening program utilizing propane as fuel, but some work was also done with JP-7 and JP-4 liquid fuels. The experimental work confirmed the general feasibility of the approach, led to the selection of Cyanamid's AERO-BAN^{R} catalyst as the most suitable of those studies, and provided some preliminary data on the kinetics of the reaction. Two general reactor design concepts were proposed, one a radial design in which the gas stream flows outward from a cylindrical core through a single catalyst bed, and the other a segmented reactor design in which the gas stream flows through a number of catalyst beds in series, with cooling between beds to remove the heat of reaction.

The objective of the present reactor design analysis program was to study several design concepts in more detail in order to obtain a preliminary assessment of the effects of bed configuration and operating parameters on system performance. System characteristics of prime concern in this study were:

- Weight
- Pressure Drop
- Safety
- Reliability
- Simplicity of Control

In this preliminary analysis, only "steady-state" performance was considered for mathematical treatment. Analysis of the transient response of the reactor system to changes in demand for ballast gas required by the varying operational modes of the aircraft was not attempted because of the limited scope of the present program. Such an analysis would be desirable in connection with possible future "breadboard" studies of this system.

3.2.1. Basic Design Concepts Studied

There are several basic conceptual approaches to the design of a catalytic reactor for reducing the oxygen concentration of ballast air to safe levels. These may be stated as alternatives, as follows:

1) Recycle or once-through flow

2) Single or multiple catalyst beds

3) For multiple-bed configurations, series or parallel flow. Split-air or split-fuel feed

In choosing among these approaches, a major consideration is the extreme exothermicity of the oxidation reactions involved, and the need for effective heat management to maintain adequate temperature control. It is also important from the standpoint of safety to ensure that the concentration of oxygen and/or fuel is maintained outside the limits of flammability in all parts of the system. When these criteria have been satisfied, attention may be focused on means for minimizing system weight and pressure drop.

Management of the heat of reaction may be accomplished in at least three ways:

1) Recycling of inerts to moderate the reaction by providing a heat sink.

2) Inter-cooling between catalyst beds in a series configuration.

3) Direct cooling within the catalyst bed.

Recycling of inerts is an attractive approach because in addition to aiding heat management it also provides a means for reducing the oxygen concentration to levels which are safely below the flammability limit (about 8-9% at reactor inlet conditions). With recycle, a single bed, or a multiple-bed series or parallel flow configuration may be considered. In a series-bed configuration with recycle, splitting the air flow among the beds also helps reduce oxygen levels throughout the system.

Without recycle, (and without direct cooling of the catalyst), a multiple bed series configuration with a limited flow of fuel to each bed is required in order to maintain catalyst temperatures within tolerable limits. Because the number of beds in series would be large (on the order of 10 or more), such a system would tend to be quite complex from the control standpoint.

Direct cooling of the catalyst bed is, in principle, an attractive means for controlling the reaction exotherm. However, preliminary design analysis carried out previously * indicated that the heat transfer surface required would be large relative to the volume of catalyst, so that this approach would require dilution of the catalyst, and thus impose a weight penalty. Another problem with this configuration is to provide uniform bed cooling. Since reaction rate is strongly dependent on temperature, it is important that the temperature level in the bed, on a plane normal to the flow, is held uniformly within a narrow range. If one area of the bed is overcooled the reaction rate will decrease. This will in turn result in a further reduction in temperature possibly to the point where reaction ceases in that portion of the bed.

In a series-bed configuration with recycle, it is possible in principle to operate outside the region of flammability by limiting the flow of either air or fuel to each reactor bed (split-air or split-fuel concept). The former leads to fuel-rich mixtures, and possible "coking" problems in the reactor. The latter avoids fuel-rich mixtures, but may introduce mechanical problems with respect to distribution of fuel among the beds, as well as some ambiguity with respect to the concentration of "fuel" in various parts of the system (because of recycling unburnt fuel and partial oxidation products). Monitoring of oxygen rather than hydrocarbon levels in the inert gas supply would appear to be a more practical approach to ensuring non-flammable mixtures throughout the system. The more difficult task of monitoring hydrocarbons would have to be used in the split fuel system. Thus, despite possible problems due to coking, the split-air concept appears initially more attractive than the split fuel.

3.2.2 Selected Concept (Series-Bed Recycle System)

A careful consideration of the various factors discussed in the foregoing paragraphs led to the selection of the series-bed recycle system with split-air flow. A generalized mathematical treatment of this type of system has been made, and is presented along with computer-generated results for specific cases in the system design sections.

This concept has another advantage in that it permits the use of a simplified fuel control. Reaction rates are strongly dependent on bed temperatures. Cooling between beds with the recycle configuration provides a means for uniform bed temperature control and therefore reaction rate control. The ram air to each catalyst-bed exchanger has a separate control so that each bed can be controlled independently of the others and of the rest of the systems.

*AFAPL-TR-69-68

3.3 Cooling and Moisture Removal Sub-System Concept

In addition to the need to provide gas low in O_2 to the tank is the requirement that the gas have relatively low moisture content. Previous systems which have used products of combustion as a source of inert gas have considered chemical drying agents or absorbents to meet this latter requirement. These types of systems are very heavy and/or require considerable maintenance. In this system, moisture is removed by condensation. The cooling required for this condensation is provided by typical aircraft refrigeration equipment and is therefore lightweight and current technology hardware.

3.3.1 Configuration for System

The heat sinks which are used are both ram air and fuel. Ram air is the primary sink and is used at all conditions. At extreme flight conditions where ram air is too hot, it is supplemented with fuel. Both the ram air and fuel heat sink requirements are minimized by the use of the condensate itself as an additional heat sink.

The moisture removal sub-system is illustrated in the system schematic in Figure 1. Inerted gas from the combustor is first precooled with ram air. It then flows through the fuel exchanger where it is cooled when ram temperatures are high. In the outlet header of each of these two heat exchangers there is a water drain which removes most of the water which is condensed in each. After leaving the fuel exchanger the inerted gas is further cooled in the regenerative heat exchanger and all of the remaining condensate is removed in a water collector located in the outlet header of the regenerative heat exchanger. The gas is then cooled in the expansion turbine which is, indirectly, the source of cooling for the regenerative heat exchanger. The energy extracted from the gas in the turbine is absorbed by the recirculating fan and is thereby rejected to the ram air. Upon leaving the turbine, all of the inerted gas including the moisture which was condensed in the turbine is passed directly into the cold side of the regenerative heat exchangers. This cooled gas, and the moisture in it, is the heat sink for the regenerative exchangers. The moisture, which is in the form of very fine fog particles, evaporates as the surrounding gas is heated in the exchanger and at the heat exchanger outlet there is no free moisture. The temperature is, in fact, well above the dew point and, when the system is operating in the low flow mode, the gas is in proper condition for pressurizing and inerting the fuel tanks. The demand fuel tank pressurization control feeds only that portion of the inerted gas required for pressurization or purging into the

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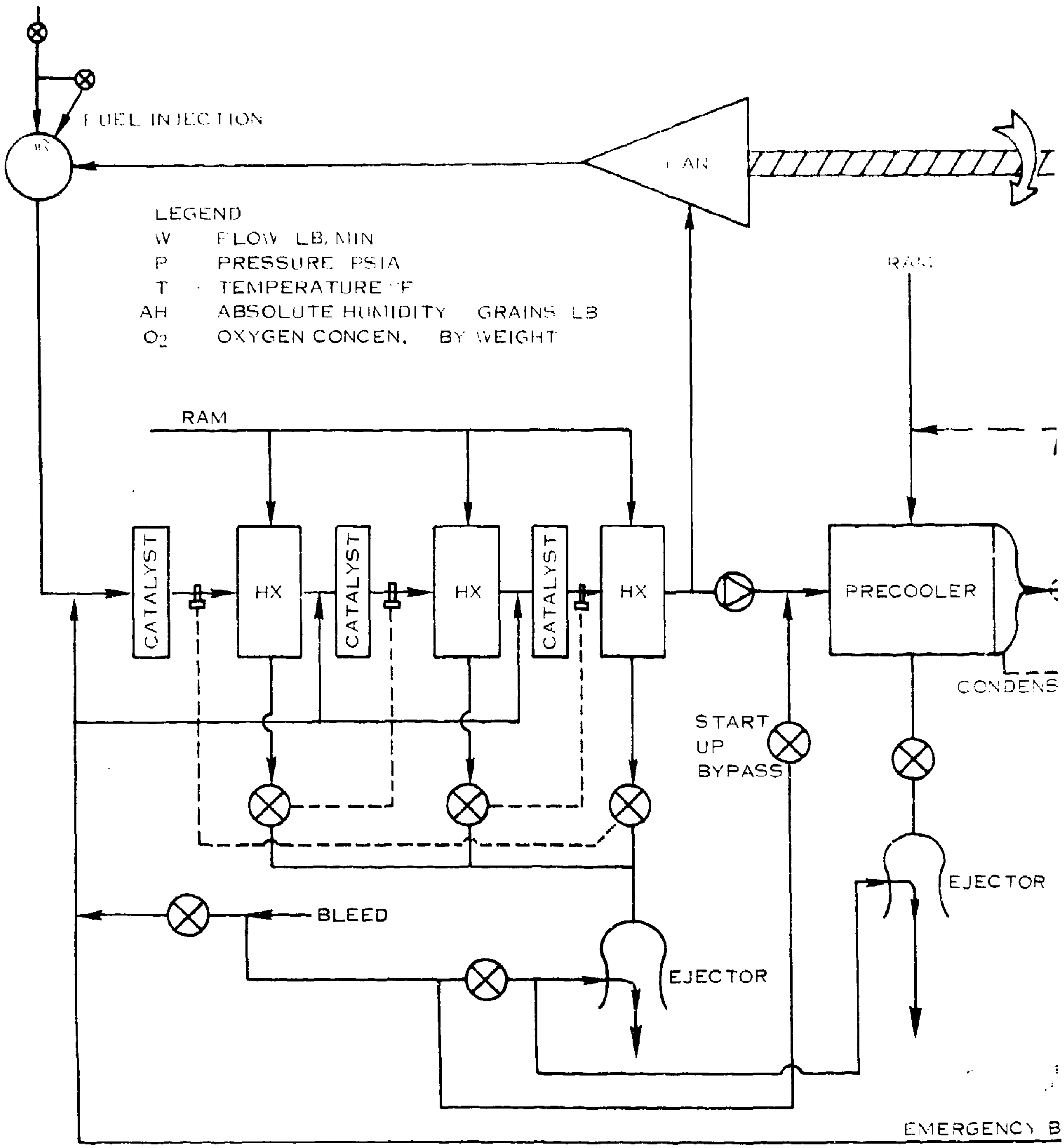

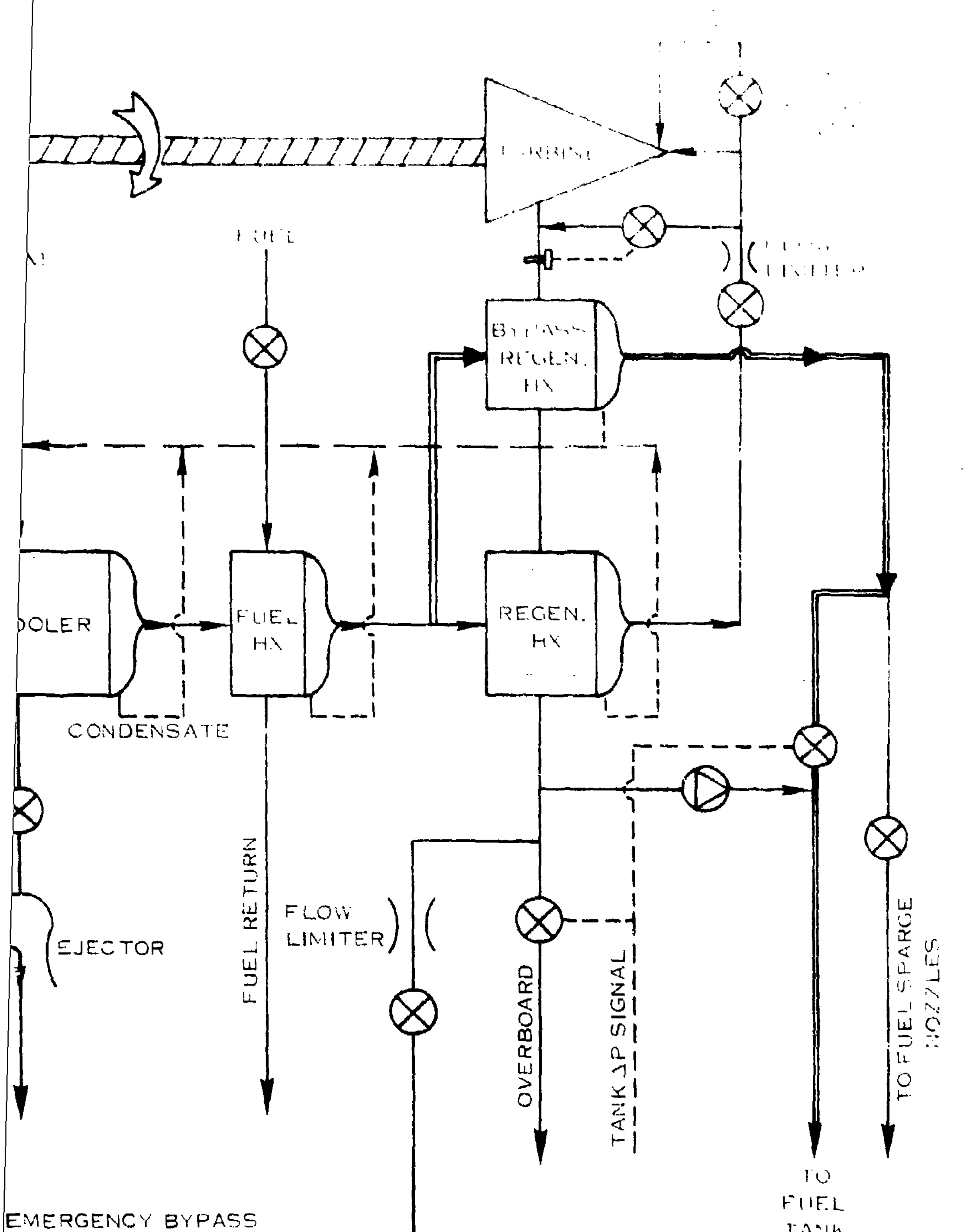

FIGURE 1. FUEL TANK INERTING SYSTEM SCHEMATIC

tanks and the remainder is discharged overboard.

For operation in the low flow mode a second regenerative heat exchanger has been added which yields substantially dryer gas. In this mode, the amount of gas required for pressurization and purging is tapped off just downstream of the fuel heat exchanger. Because of the favorable mass flow ratio substantially colder, and therefore dryer, air is possible. In this case the demand control system throttles the inert gas stream to maintain the necessary flow rate. Turbine effluent is discharged overboard under this mode and consequently turbine discharge pressure is closer to ambient pressure rather than fuel tank pressure. This lower turbine discharge pressure is another factor which contributes to the lower moisture content.

3.3.2 Alternate Systems Studies

Systems studies which were conducted in establishing this system included several alternate configurations. Three of these warrant further discussion. An alternate turbomachinery configuration was examined which used a portion of the turbine power to raise the system pressure level. Although the higher pressure aided the moisture removal, this approach was discarded because it had insufficient power for the recirculating fan. In the selected system the condensate is used as a heat sink by being sprayed into the ram air of the precooler. This approach was selected over the direct boiling of the water in a separate heat exchanger because it yields a lower temperature sink and it eliminates the need for an additional heat exchanger. Lastly, a system was considered which used a water separator downstream of the turbine. Superficially, this would appear to be a better system thermodynamically because it permits a higher turbine inlet temperature for a given supply moisture level. Were it not for the increased pressure downstream of the turbine resulting from the water separator pressure drop this alternate system would be superior, but the decreased turbine pressure ratio more than offsets the advantage of the higher allowable inlet temperature. A substantial pressure drop is required in the water separator because of the fineness of the water particles that exist at the turbine outlet. These particles are on the order of one micron in size and must be coalesced before they can be mechanically separated.

3.4 System Control Selection

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3.4 System Control Selection

3.4.1 Control Philosophy

The performance requirements for the system cover a very wide range of operating conditions. Inert gas flow requirements range from one lb/min at most conditions to 50 lb/min at other flight conditions and to 200 lbs/min at emergency descent conditions. Generally speaking, these conditions can be grouped into the two ranges; the higher occurring at descent and the lower range at all other conditions. As discussed in the section on system description, there are two modes of operation which have been selected. The control philosophy was to minimize the complexity by making these the only modes that need be considered. More complex control concepts were considered in the study but were found to be of little advantage. The magnitude in flow rates at which acceptable turbine performance could be achieved was actually the determining criteria in setting the flow level at the low flow mode. As described in the earlier sections, the system was designed for the descent requirements. System studies showed that, to get proper oxygen and moisture levels, a minimum turbine nozzle area of 10% of the design area must be maintained. Since all operating conditions other than descent required less than 10%, it was permissible to adopt a control scheme which would waste the difference in these flow requirements and the 10% level. This excess flow has been used to good advantage to provide drier inert gas. A similar philosophy (minimum complexity) has been used in the concepting of the other controls. Wherever a control has a minimum effect on system weight and aircraft penalty, the simplest control approach has been used. In other areas, such as in the control which regulates the supply of inert gas to the fuel tanks where the control has a significant effect on fuel tank inerting conditions, a somewhat more complex control has been used.

In some control elements there are uncertainties of the criticallity of their influence on system operation. In these areas where it will be necessary to have experimental data to resolve these uncertainties, the simplest control approach has been used. The controls which fall in this latter category include start-up controls, the fuel flow rate controls, and the reactor-bed temperature controls.

Despite these simplifications to the controls, the resultant system requires relatively complex controls. The wide variety of parameters which must be controlled make this necessary. Relief in system requirements and changes to the system schematic offer the possibility of further control simplification. For the current requirements however, these controls are essential to proper operation.

In addition to these controls, a means of monitoring O_2 concentration should be included in the final system. Such a device has not been included in this study because it would not have a control influence on the system. It would be used to sense the oxygen concentration to indicate when the specified limit was exceeded and thereby indicate when catalyst regeneration or replacement was necessary.

3.4.2 Selected Controls

The moisture removal subsystem incorporates three basic control functions; a control in the precooler to minimize ram air consumption and the corresponding penalty, a control on the fuel flow to minimize heat addition to the fuel, and a control to prevent snow at the bypass regenerative heat exchanger cold-side inlet. The precooler ram air control limits ram flow to maintain a minimum hot-side outlet temperature of 90°F. In addition to minimizing ram flow, this control also eliminates the possibility of freezing in the precooler on cold days. There is an additional function of this control which limits the ram air control valve maximum area to five square inches when the system is operating in the low-flow mode. This area is sufficient to maintain maximum precooler effectiveness when in this mode. The fuel heat exchanger control is a simple on-off control which turns on the fuel flow to the exchanger when the ram air temperature is above 150°F. Freezing conditions entering the regenerative heat exchanger are prevented with a bypass around the turbine which maintains a temperature of 35°F at that point. A venturi is located upstream of the bypass line to limit the flow in the high flow mode when bypass is occurring.

The catalyst-bed subsystem controls are simply the two-level fuel flow corresponding to the high - and low-flow modes and the bed temperature controls. The latter controls modulate ram air through each heat exchanger to maintain the temperature leaving the succeeding bed to a prescribed level. It has been necessary to use a separate control on each bed because of the criticality of maintaining proper catalyst temperatures. The experimental data on the catalyst shows very vividly the strong influence of bed temperature on reaction rate. A single control on all three beds could not hold the desired bed inlet temperatures and corresponding heat fluxes over the range of steady-state and transient flight conditions. This influence of temperature on reaction rate is typical of catalyst reactions and is not restricted to this geometry.

The system includes two additional controls. One is for start-up and consists of a bypass valve around the catalyst bed. This provides direct bleed air to the cooling turbine for driving the recirculating fan. The

second control is an emergency bypass valve which feeds bleed air directly to the fuel tank pressurization line for supplemental flow during rapid descent.

3.5 Comparison of the TFA and the B-1 System

Schematically, the TFA system is identical to the B-1 system with the exception of one control function. In the TFA system there is an added control function which will switch the system to the high flow mode at the time the aircraft weapons are aimed. This will provide maximum flow availability instantaneously during combat maneuvers. Upon safetying weapons, the control will switch back to the normal mode, which will be either high-or low-flow, depending on the flight condition.

Performance of the TFA will be similar to that on the B-1, with the flow reduced to approximately 6% at all conditions. The system weights will be reduced correspondingly.

4.0 SYSTEM OPERATION

4.1 Start-up

Normal operation of the fuel tank inerting system may be assumed to begin with a start from a cold condition. Also, it is reasonable to expect that the system is filled with air as a result of leakage transfer with the atmosphere during the shutdown period. Once operational, the system is designed to run continuously. If, however, a shutdown occurs, the re-start procedure would follow the same sequence as that for a cold start since it is likely that the system would cool down and fill with air as a result of a shutdown.

The start-up procedure to be followed involves a sequence of events observed to be necessary to accommodate the basic nature of the catalytic inert gas generator. Specifically, a heat-up period is required before the inerting reaction can be initiated. When the so-called "light-off" temperature is attained, the rate of fuel addition to the heated air must be low enough to enable the reactor cooling system to maintain control over catalyst temperature. Running the catalyst on a pure air/fuel mixture leads to essentially full oxidation of the fuel in the first catalyst bed encountered. This, in turn, could lead to a rapid overheating in the first catalyst if excessive fuel was available. An initial mixture of approximately 1.0% fuel in air (by weight) is dictated by analysis.

The sequence devised to achieve the desired system start-up characteristic is outlined below. Since normal start-up is envisioned for ground operation, bleed air is assumed to be flowing to the ejectors.

a. The reactor bleed supply valve is closed and the start-up bypass valve is opened.

   Thus, the system begins operation with air driving the cooling turbine and the gas stored in the reactor, essentially entrapped in the recirculating loop with no fresh bleed air being added. Also, no fuel is being injected.

b. The recirculating flow is heated to 500°F.

   This represents what may be considered a minimum "light'off" temperature for the catalyst employed. The actual heating of the system is partially accomplished through the heat generated

by the fan. This is supplemented by an electric heater which locally heats the first catalyst bed. The required size of the heater would depend on the desired start time. Without the electric heater, start-up time would be 10 to 15 minutes from a cold soak condition.

c. Fuel flow commences at a mass flow rate of approximately 0.5 lb/min, corresponding to approximately 1% of the recirculating flow rate.

The oxygen in the recirculating flow is thus consumed as reaction is initiated. Cooling flow to the reactor heat exchangers is available as becomes necessary. This part of the start-up sequence would last for a predetermined time aimed at inerting the atmosphere within the recirculating loop before fresh bleed air is added.

d. The start-up bypass valve closes as the reactor bleed supply valve opens and the fuel injection rate is adjusted to correspond to bleed flow.

Normal operation of the system is thus established. During this start-up procedure the fuel tank pressure control system will be functioning, passing most of the system flow overboard.

As indicated above, considerable detailed design analysis, as well as experimentation, remains to be done in order to describe the system start-up characteristic precisely. Establishing this characteristic would be included in a suggested follow-on to this preliminary design program.

4.2 Steady-State

In order to accommodate the wide range of inert gas flow requirements encountered over a flight profile, the system operates according to a high/low-flow mode control which allows adequate flows to satisfy the high demand of descent while attempting to minimize the penalty of continuous operation during periods of low-flow demand. The system will normally be operating in the low-flow mode. This means that normally only 10% of the full turbine nozzle area will be utilized and the ram flow through the precooler will be restricted by closing the discharge valve to a position providing approximately 5 in^2 effective flow area. Also, in the low-flow mode, only the small fuel nozzle will be in use supplying fuel to the combustor. Furthermore, in the normal low-flow mode, the inert gas flow to the fuel tanks is tapped from upstream of the regenerative

heat exchanger, cooled and dehumidified in the bypass regenerator and throttled at the tank pressure control valve. The remaining system flow is spilled overboard.

The switching from the normal low-flow mode to the high-flow (or descent) mode is accomplished by the use of a pneumatic rate detector which is sensitive to rate of change of ambient pressure. During descent, a signal will be provided that would cause the following changes to occur:

a. The valve at the turbine inlet would open, allowing full admission to the turbine nozzles.

b. The precooler ram air control valve would be free to operate full open.

c. The reactor fuel supply would be increased by permitting flow to the large, as well as the small, fuel spray nozzle.

d. The fuel tank pressure control function would switch from the fuel tank pressure control valve to the overboard spill valve.

e. The reactor bed temperature control would switch setting from 1100°F to 1337°F.

The signal to switch would be overridden by an altitude bias since the fuel tank pressure is maintained constant above 25,000 feet. Hence, changes in ambient pressure would not affect fuel tank pressure until the descent passes through that altitude.

4.3 Shut-Down

Prior to the shutdown of the aircraft bleed air supply, inerting system shut-down control will sequence the removal of the fuel and air supplied to the catalytic reactor. The fuel supply will be shut off first, allowing for a short operating period with air only. This procedure serves several purposes. As long as the catalyst beds remain hot enough, reaction will continue to purge the system of fuel vapors and to provide a catalyst regeneration period wherein any coke deposited upon the catalyst surface would be burned off. Once all reaction is completed, the bleed air flow will provide a means of cooling the inerting system. Also, operation for a

short time without reaction would allow the moisture removal subsystem to run relatively dry. This would provide for drying the components which normally run wetted by acidic condensate from the products of reaction.

During the shut-down period, all control systems will be operating. Since normal shut-down will be executed on the ground, cooling by means of the ejectors will be available. The fuel tank pressure control will pass most of the system flow overboard so that the shut-down period would not serve to significantly increase the oxygen concentration in the fuel tanks.

5.0 SYSTEM DESIGN

This section contains a detailed description of the various components of the system which have been designed to meet the specified requirements of the B-1 and is based on the selected system schematic. A detailed design analysis of the catalyst has been included which can be correlated with the experimental portion of this program. Installation-type drawings are presented on the major components. Since particular installation requirements will have a direct influence on the shape of many of these components, these drawings should be considered to be merely typical. Further system or component optimization will also have some effect on the size and shape of each. The weight summary reflects a moderate amount of optimization, and the installation drawing represents one possible arrangement of these typical sizes.

5.1 Materials Selection

Hamilton Standard conducted an extensive study * several years ago into the best material for use in a gas turbine recuperator. The availability, corrosion resistance, and mechanical property requirements explored in this study are very similar to those of the inerted gas portion of the Fuel Inerting System.

The following is a summary of the recuperation requirements and conclusions. The characteristics considered necessary for this application are as listed below:

a. Availability:

The material must be available in cold-rolled, pickled and annealed sheets and foils of the required thickness and must be economical commensurate with other requirements.

b. Corrosion Resistance:

(1) Elevated Temperature Oxidation - The material must have superior resistance to elevated temperature (500-950°F) oxidation.

(2) Products of Combustion - The material must have superior resistance to oxidation and reduction resulting from the products of combustion and breakdown of JP-5 or diesel fuel at operating temperatures from 500°F to 950°F.

* Hamilton Standard Technical Study for Marine Gas Turbine Recuperators, EP 64304, March 5, 1964

(3) Salt Water Pitting - The material must be resistant to pitting induced by the presence of stagnant salt water of varying concentrations. (This is a result of salt atmosphere contamination during recuperator shut-down periods.)

(4) Chloride-Ion Stress Corrosion Cracking - The material must have superior resistance to chloride-ion stress cracking at temperatures of 500-950° F because of salt water ingestion. (The required brazing alloys and welding filler rods must be equally resistant to the above corrosion environments.)

c. Mechanical Properties:

(1) Tensile Properties - Must be considered good over the entire operating and transient temperature range (room temperature to 1350° F).

(2) Short-Time Creep and Stress Rupture Properties - Must exhibit high values at temperatures up to 1350° F.

The combined corrosion resistance and mechanical property requirements complicated the material selection since all of these requirements are not generally encountered together. The groups of materials considered for single or partial combinations of the above requirements were investigated for applicability to this recuperator program. They were as listed below.

Titanium and Titanium Alloys
Inconel Alloys
Incoloy Alloys
Ni-O-Nel Alloys (Nickel-Iron-Chromium)
Monel Alloys
Copper-Nickel Alloys
Electrolytic and Electroless Nickel Plate on high strength, low alloy steels

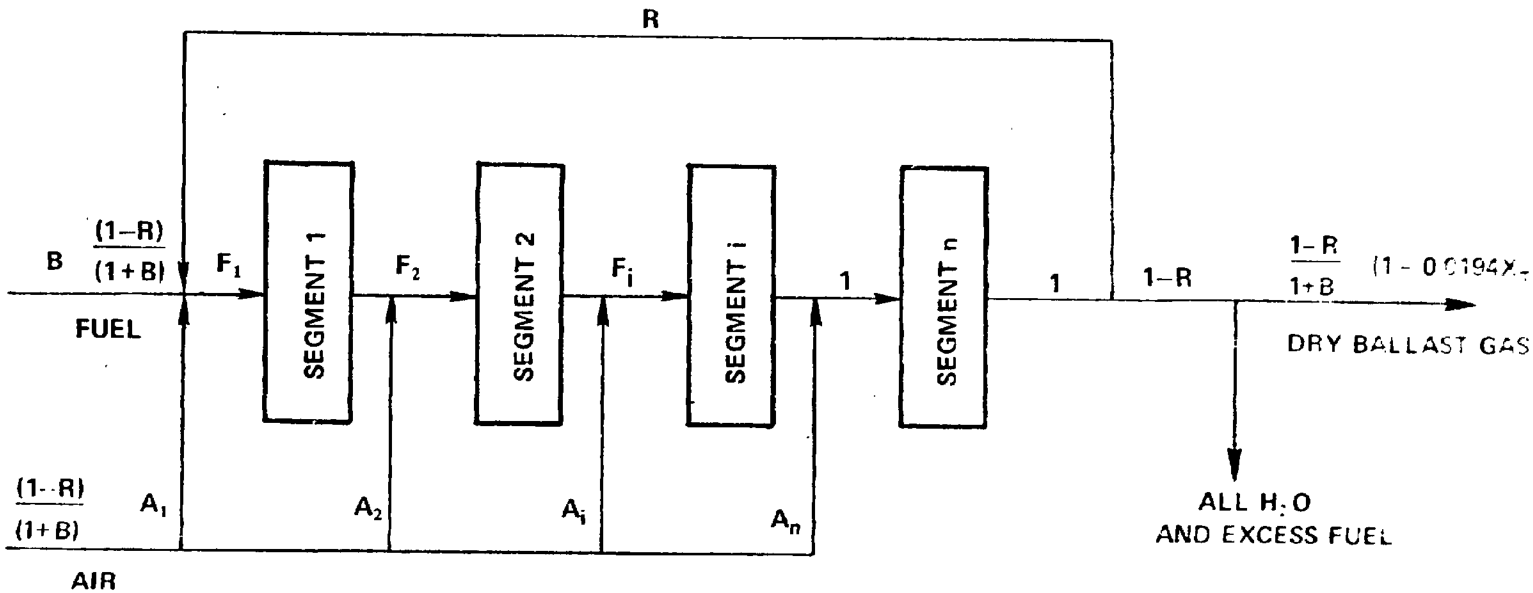
Low alloy steels were not considered due to their low resistance to high temperature oxidation, while stainless steels (austenitic and martensitic) were not considered because of their high susceptability to stress corrosion cracking. The relative ratings of the various materials considered are presented in tabular form below. The results of these studies indicate that Incoloy 800, Titanium Alloy 600 are both suitable, considering their corrosion resistant characteristics. However, since Incoloy 800 is the best from a fabrication viewpoint, it was chosen for this application.

Material	Avail-ability	Corrosion Resistance: Elevated Temp Oxidation	Corrosion Resistance: Products of Fuel Combustion	Corrosion Resistance: Salt Water Pitting	Corrosion Resistance: Stress Corrosion	Elev Temp Mechanical Properties
Copper-Nickel Alloys	Good	Poor	Unknown	Excel	Excel	Fair
Monel Alloys	Good	Unknown	Poor	Excel	Fair	Good
Nickel Plate on High Strength-Low Alloy Steels	Excel	Poor	Poor	Good	Unknown	Good
Inconel Alloys	Good	Excel	Good	Good	Excel	Excel
Incoloy Alloys	Good	Excel	Excel	Excel	Excel	Excel
Ni-O-Nel Alloys	Fair	Excel	Excel	Excel	Good	Good
Titanium Alloys	Good	Fair	Excel	Excel	Excel	Excel

For the Fuel Tank Inerting System, all components exposed to the products of combustion or the resulting acids will be fabricated of Incoloy 800 or, in cases where higher strength or castings are required, of Inconel alloys unless otherwise stated in the individual component description.

5.2 Catalyst-Bed Design Analysis

The mathematical analysis of the series-bed recycle system was based on the schematic diagram presented in Figure 2. For convenience, the analysis was carried out on the basis of 1 lb/hr of wet gas leaving the final reactor segment, with an appropriate scale factor being applied to translate the results to the specific ballast gas demand for a given aircraft and operational mode. Details of the calculation methods are presented in Appendix I, so that only a brief explanation of the approach is given here.



BASIS: 1 lb/hr WET GAS LEAVING THE FINAL REACTOR SEGMENT

R = RECYCLE RATIO
B = OVERALL FUEL/AIR RATIO, lbs./lb.
A_i = AIR INPUT TO INDICATED REACTOR SEGMENT, lbs./hr.
F_i = TOTAL GAS FLOW THROUGH INDICATED REACTOR SEGMENT, lbs./hr.

FIGURE 2. FLOW SCHEMATIC, SEGMENTED REACTOR FOR FUEL TANK INERTING

5.2.1 Design Approach

The methods used to calculate the steady-state performance of this system involve four basic relationships;

- material balances around the total system and around each reactor segment individually
- heat balances around each reactor segment (assumed to be adiabatic)
- a chemical reaction rate expression
- an empirical relationship for estimating pressure drop through the catalyst beds

The first two relationships describe how the system functions in terms of flow rates, conversion levels, and temperature rise in each of the component segments. The amount of catalyst required is then calculated from the reaction rate expression. Based on earlier studies, a pseudo-first order rate expression of the type $K_T = SV\ (\ln \frac{1}{1-X})$

was used. This expression states that at a given temperature (taken as the reactor "hot-spot" temperature in this application) the product of the space velocity (SV) and a function of fractional oxygen conversion (X) is constant (the reaction rate constant, K_T). Space velocity is defined as the volume of gas flowing per unit time per unit volume of catalyst, and thus may be considered as the reciprocal of the "residence time" in the reactor. When conversions and flow rates are known, space velocities and hence, catalyst weights, may then be calculated for each reactor segment. For the preliminary design studies reported here, a reaction rate constant of 194,000 hr^{-1} at a catalyst "hot-spot" temperature of 1337°F (725°C-the maximum allowable operating temperature for the catalyst) was used. It is important to note that the rate constant is a strong function of temperature (decreases at lower temperatures). Throughout this analysis, the implicit assumption is that inlet temperatures to each reactor segment will be adjusted so as to maintain the reactor hot-spot at the specified temperature at all times.

The pressure drop expression utilized in this analysis is based on correlations reported in the literature for flow through packed beds. Adapted to the present application it takes the form:

$$P = K\left(\frac{T_{ave}}{P_{ave}}\right)(SV)^{1.85}(\ell)^{2.85}$$

indicating that the pressure drop in each segment is an exponential function of space velocity and bed thickness (ℓ), but is independent of the scale of operation.

5.2.2 Design Parameters

For the system as depicted in Figure 2, assigning values to the following major parameters (independent variables) is sufficient to fix the system *.

- number of beds in series
- recycle ratio
- overall oxygen conversion
- air flow coefficients (describing the distribution of bleed air among reactor segments)
- conversion coefficients (describing how the total amount of conversion is to be apportioned among the beds)

With these inputs, the following dependent parameters may then be calculated for each reactor segment:

- conversion level
- oxygen concentrations entering and leaving
- temperature rise
- catalyst weight
- catalyst cross-section
- pressure drop

The above represents a "general case". Obviously, there are many possible combinations of the independent variables (particularly with regard to the distribution of air flow and conversion among beds), so that an extremely large number of reactor configurations could be calculated. In practice, it may be desirable to place other restrictions on the system. For example, if the amount of conversion in each bed is assumed to be proportional to the flow through that bed, the temperature

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* Assuming that the ballast gas demand, reaction rate constant, overall fuel/air ratio, average pressure and minimum catalyst bed thickness have been specified.

rise in each bed at design flow will be equal and may be specified. Similarly, the air flow distribution may be made proportional to the total flow through each bed (so that the temperature rise in each bed would be approximately equal at low flows when conversion in each bed approaches 100%). When the above restrictions are applied, and a temperature rise is specified, the required recycle ratio may then be treated as a dependent variable.

Six computational cases have been programmed for solution by the computer. These cases differ with regard to the variables which are specified, and the restrictions which apply, as shown in Table I. Case 6 is of particular interest in that it can be used to determine the effect on system performance of changes in parameters once the catalyst-bed weights have been determined for a previous set of parameters.

In the following section, the results of a series of computer runs based on several of the cases listed in Table I are presented and discussed.

5.2.3 Results and Discussion

a. General Parametric Study

Tables II and III summarize the results of the computer runs made in the course of this analysis. (Detailed results, in the form of computer printout sheets, are given in Appendix II.) The runs in Table II were made to determine the general effects of variations in specific parameters. Catalyst weights and bed areas are scaled to a ballast gas demand of 80 lbs/min for the B-1 bomber. First, a series of runs was made using computer case 3 to explore the effect of variations in conversion level, number of reactor segments, and the recycle ratio. In this series, the air flow was assumed to be split equally among beds. Temperature rise at design flow was held constant among reactor segments in any one run, but varied among runs with variations in the other parameters.

Another series of runs was made using computer case 4. In this case, air flow was distributed in proportion to the total flow through each segment. For many of the runs in this series, the temperature rise at design flow was fixed at 595°F, which would be near the maximum tolerable temperature rise, assuming a gas inlet temperature of about 700°F.

TABLE I: CASES PROGRAMMED FOR COMPUTER SOLUTION

Case Number	1	2	3	4	5	6
SPECIFIED VARIABLES						
Number of Reactor Segments	x	x	x	x	x	x
Recycle Ratio	x		x		x	x
Overall Conversion	x	x	x	x	x	
Air Flow Coefficients	x	x	x			x
Conversion Coefficients	x					
Temperature Rise at Design Flow		x				
Temperature Rise at Low Flow				x		
Catalyst Weights						x
RESTRICTIONS						
Conversion proportional to total flow in each bed (ΔT at design flow equal for all beds)		x	x	x	x	
Air flow proportional to total flow in each bed (ΔT at 100% conversion equal for all beds)				x	x	

TABLE II: DESIGN CALCULATIONS: GENERAL PARAMETRIC STUDIES[1]

Computer Run No.	No. of Beds in Series	Recycle Ratio[2]	Overall Conversion, %	Temperature Rise in Reactor Beds, °F: Design Flow[3]	Temperature Rise in Reactor Beds, °F: Low Flow[4]	Oxygen Concentration, Wt %: Entering[5]	Oxygen Concentration, Wt %: Leaving[6]	Average Space Velocity, hr^{-1}	Total Catalyst Weight, lbs.	Total Pressure Drop, psi[7]	Catalyst Bed Cross-Sectional Area, ft^2[7]
Case No. 3: Air Flow split equally among beds.											
1	3	0.65	90	520	655[4]	4.9	2.1	255,000	54.5	1.2	7.0
2	3	0.65	86	495	655	5.8	3.1	350,000	61.5	2.1	5.2
3	3	0.65	81	465	655	6.7	4.1	450,000	47.5	3.3	4.0
4	3	0.65	76	440	655	7.5	5.2	565,000	38.0	5.0	3.2
5	2	0.75	81	475	625	6.6	4.1	435,000	48.5	1.7	6.6
6	4	0.56	81	465	705	6.8	4.1	465,000	46.5	5.9	2.8
7	3	0.55	81	620	915	7.7	4.1	370,000	44.0	2.7	3.5
5A	3	0.75	81	320	435	5.8	4.1	605,000	51.5	[illegible]	4.6
Case No. 4: Air Flow to each bed in proportion to total flow through that bed.											
16	3	0.59	95	665	700	4.3	1.1	140,000	128.0	0.37	10.7
8	3	0.59	85	595	700	6.1	3.3	300,000	59.0	1.6	5.5
17	3	0.59	75	525	700	7.9	5.4	490,000	36.0	4.0	3.0
18	3	0.59	65	455	700	9.6	7.6	740,000	23.5	5.7	2.1
21	1	0.84	85	595	700	6.2	3.3	300,000	58.5	0.35	17.2
14	2	0.71	85	595	700	6.1	3.3	300,000	58.5	0.82	8.0
15	4	0.49	85	595	700	6.0	3.3	295,000	59.5	2.7	3.5
10	6	0.34	85	595	700	5.9	3.3	295,000	60.0	6.7	2.1
23	1	0.82	75	595	795	8.4	5.4	450,000	34.5	0.66	10.2
24	3	0.55	75	595	795	8.2	5.4	445,000	35.0	3.5	2.9
20[8]	3	0.59	85	595	700	6.1	3.3	231,000	76.5	1.0	6.4

Notes: (1) For all runs, the following values are fixed:
Ballast gas demand = 30 lbs/min.
Fuel/air ratio = 0.0746 lbs/lb
Minimum bed thickness = 1 inch
Average system pressure = 50 psia
Reaction rate constant = 194,000 hr^{-1}, except as noted.
Conversion in each bed at design flow proportional to total flow through that bed.

(2) Recycle ratio assumed constant and equal for both high and low flow modes.

(3) Temperature rise equal for all beds.

(4) Temperature rise assuming conversion approaches 100% at low-flow condition (one-tenth design flow). For Case 3, value given is for the first bed; temperature rise in subsequent beds is lower.

(5) Entering first reactor bed.

(6) Concentration in wet gas leaving final reactor bed. Value on dry basis would be about 10% higher.

(7) For 1" minimum bed thickness, constant cross-section for all beds.

(8) Reaction rate constant assumed = 150,000 hr^{-1}.

TABLE III: DESIGN CALCULATIONS: SPECIAL RUNS(1)

Computer Run No.	Ballast Gas Demand, lbs/min.	Recycle Ratio	Overall Conversion, %	Bed Number	Temperature Rise in Reactor Beds, °F	Oxygen Concentrations, Wt. %: Entering	Oxygen Concentrations, Wt. %: Leaving	Space Velocity, hr^{-1}	Catalyst Weight, lbs	Pressure Drop,(2) psi	Comments
Case No. 6: Catalyst bed weights specified. Air flow distribution: 28% to first bed, 33% to 2nd bed, and 39% to 3rd bed (same as in Run 8, Table II), except as noted.											
9	80	0.60	84	1	660	6.1	2.9	260,000	20	0.24	Similar to Run 8, but with equal catalyst weights for each bed.
				2	565	5.8	3.0	300,000	20	0.32	
				3	515	6.0	3.4	350,000	20	0.44	
									60	1.0	
12	200	0.375(3)	66	1	1030	11.3	6.2	325,000	20	0.37	Same as Run 9, but with ballast gas demand corresponding to emergency descent.
				2	765	10.5	6.7	435,000	20	0.67	
				3	620	10.4	7.4	560,000	20	[illegible]	
									60	[illegible]	
13	200	0.375(3)	67	1	895	11.2	6.8	390,000	17	[illegible]	Same as Run 8, but with ballast gas demand corresponding to emergency descent.
				2	785	10.9	7.0	445,000	19	0.95	
				3	705	10.7	7.2	495,000	23	1.82	
									59	3.2	
22	8	0.90(4)	100	1	335	2.2	0.5	140,000	20	[illegible]	Same as Run 9, but at "low flow" condition. All air fed to first bed.
				2	85	0.5	0.1	140,000	20	[illegible]	
				3	20	0.1	0.04	140,000	20	0.09	
									60	[illegible]	
19	80	0.59	80	1	560	6.9	4.2	295,000	17	0.32	Beds sized as in Run [illegible], for k = [illegible] hr^{-1}, but assuming deactivation during operation to k = [illegible] hr^{-1}.
				2	560	7.0	4.2	300,000	19	[illegible]	
				3	560	7.1	4.3	300,000	23	[illegible]	
									59	1.6	

Notes:

(1) For all runs, the following values are fixed:
"Design" ballast gas demand = 80 lbs/min.
Fuel/air ratio = 0.0746 lbs/lb.
Minimum bed thickness = 1 inch
Average system pressure = 50 psia
Reaction rate constant = 194,000 hr^{-1}, except as noted.

(2) For 1" minimum bed thickness, constant cross-section for all beds.
(3) Recycle ratio estimated by Hamilton Standard for emergency descent mode.
(4) Recycle ratio estimated by Hamilton Standard for low-flow mode.

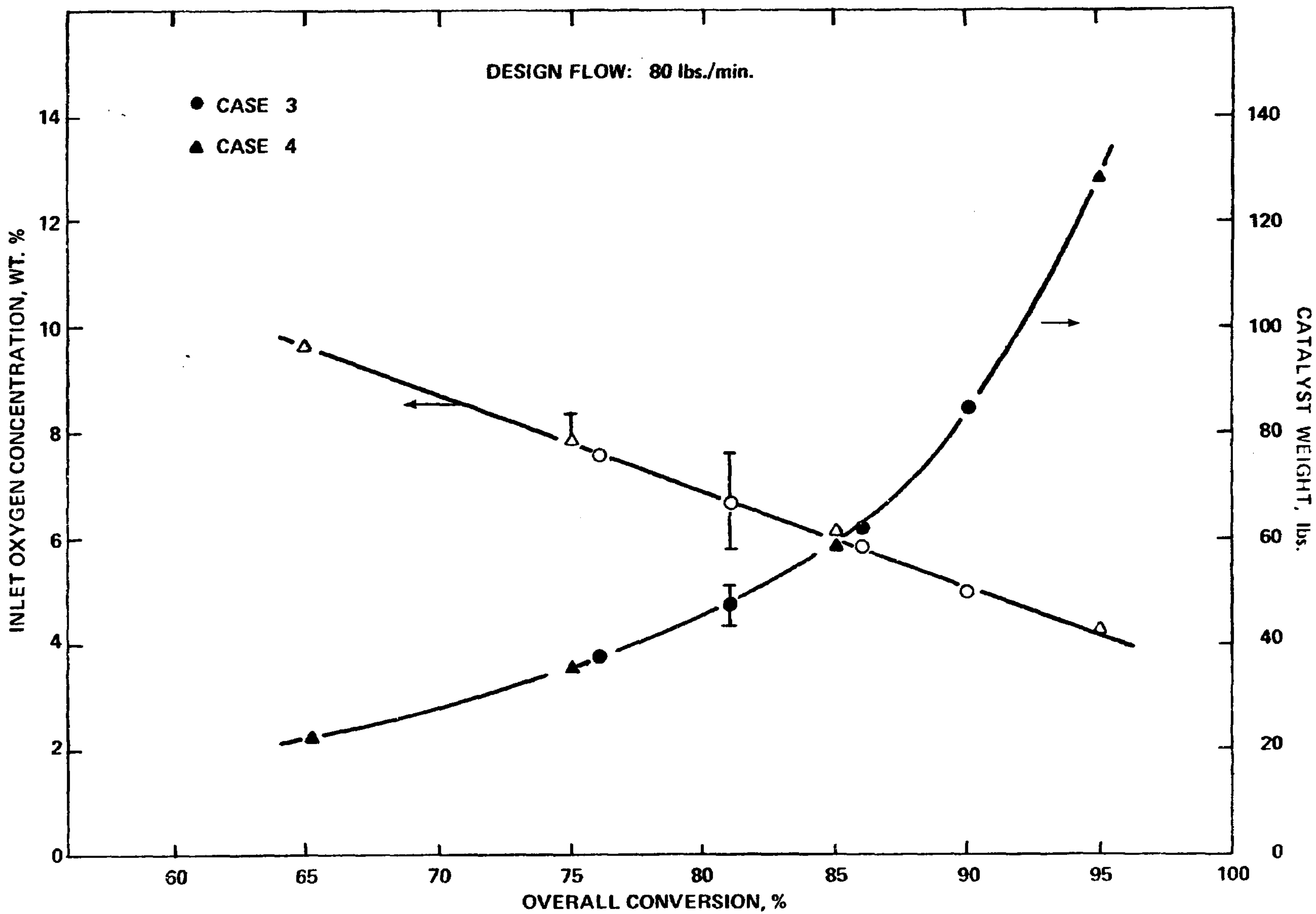


FIGURE 3. CATALYST WEIGHT AND INLET OXYGEN CONCENTRATION VS OVERALL CONVERSION LEVEL

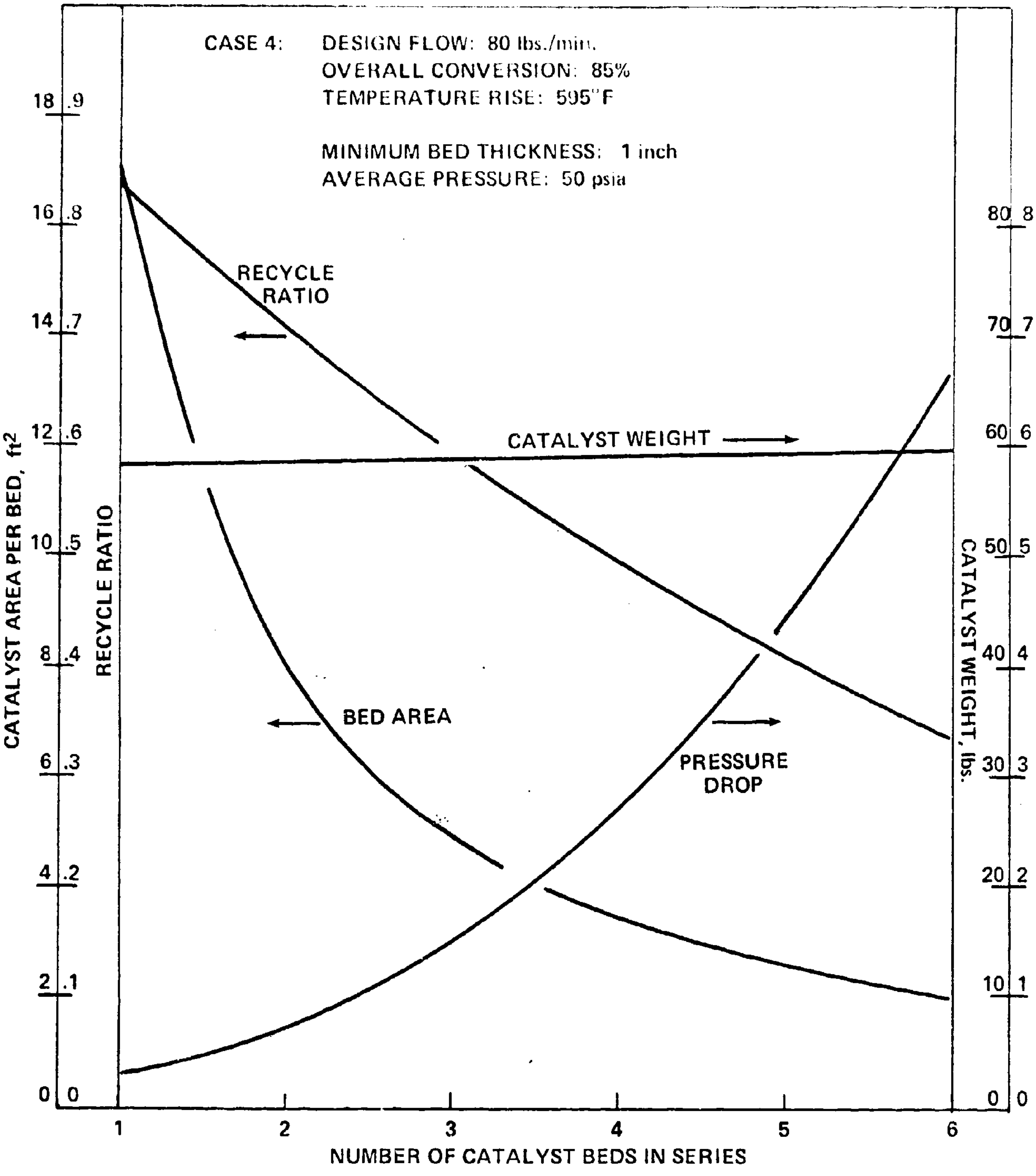


FIGURE 4. EFFECT OF NUMBER CATALYST BEDS IN SERIES CONFIGURATION

Analysis of the results given in Table II shows that both total catalyst weight and the oxygen concentration entering the first reactor stage are governed primarily by the overall oxygen conversion level, and are much less sensitive to recycle ratio or the number of beds in series. This is illustrated in Figure 3, which shows that catalyst weight increases sharply at conversions above about 85%. The range of weights indicated at 81% conversion (± about 10%) covers variations in recycle ratio from 0.55 to 0.75, in number of beds from 2 to 4, and in temperature rise from 320°F to 620°F. Catalyst weight is also inversely proportional to the reaction rate constant so that, for example, if the rate constant were actually 25% lower than the assumed value, the weight required for a given conversion would be about 33% higher. Experimental data indicate, however, that the value for the rate constant used in the design analysis ($K = 194,000\ hr^{-1}$) is approximately correct in the region of principal interest.

Inlet oxygen concentration, as expected, decreases with increasing overall conversion. (In this presentation, all oxygen values are given in weight percent. On a valume basis, the values would be about 10% lower). The exit concentration is uniquely determined by overall conversion; inlet concentration then depends on the amount of recycle and the proportion of bleed air fed to each reactor segment. If the temperature rise in each bed is to be maintained at about 600°F, the inlet oxygen concentration must be maintained at about 3% as overall conversion approaches 100%.

It is of interest to note that, for the configurations represented by the runs in Table II, the inlet and outlet concentrations were nearly the same for all of the beds in series. For example, in Run 10, with six beds, inlet oxygen concentrations ranged only from 5.9% in the first bed to 6.2% in the last. Similarly, exit concentration ranged from 3.0 to 3.3%.

Figure 4 shows how varying the number of beds in the series configuration affects the other parameters. Data for this plot were taken from the runs under case 4, with overall conversion and temperature rise constant at 85% and 595°F respectively. Note that catalyst weight changes only slightly as the number of beds is increased from one to six. Recycle rate must be decreased in order to maintain the desired temperature rise. The bed area and pressure drop curves assume a minimum bed thickness (i.e., the thickness of the smallest bed) of one inch. With bed thickness fixed and catalyst weight essentially constant, the cross-sectional area per catalyst bed is inversely proportional to the number of beds, while the pressure drop increases approximately as the square of the number of beds. If beds thinner than 1" could be utilized, pressure drop would decrease markedly, ($\Delta P \propto \ell^{2.85}$), but cross-sectional area would

increase. Where the ballast gas demand is large, as in the case of the B-1 bomber, the cross-sectional area required even at 1" bed thickness may present a significant problem with regard to obtaining uniform distribution of flow across the bed face.

Pressure drop is also strongly affected by space velocity ($\Delta P \propto SV^{1.85}$). Thus, if it is desired to save catalyst weight by operating at higher space velocities and lower overall conversions, a penalty in increased pressure drop must be accepted (assuming the number of beds remains unchanged). Compare, for example, runs 8 and 24, Table II.

Of the runs presented in Table II, run 8 appears to represent a reasonable trade-off among the various parameters. By operating at a relatively high overall conversion level (85%), it is possible to maintain low oxygen concentrations throughout the system and a reasonable pressure drop, without using an excessive weight of catalyst. This set of conditions has an advantage over other configurations involving lower overall conversions in that a greater degree of catalyst deactivation, if encountered during use, could be tolerated before the oxygen in the ballast gas reached an unsafe level. It would, of course, be possible to decrease the size of the reactor system somewhat by bypassing sufficient bleed air to bring the exit ballast gas up to about 6% oxygen, but this would eliminate the margin allowed for deactivation or other malfunction.

b. Special Runs

The general parametric study just discussed led to the selection of the reactor configuration in Run 8 as a "base" design. Several additional runs were then made to explore the effects of a slight modification to this configuration, and of operation under "off-design" conditions. The results of these runs are summarized in Table III.

Run 8 describes a three-bed series reactor, with recycle, operating at an overall conversion level of 85%, and with a temperature rise at design flow of 595°F in each bed. Because of design restrictions placed on the system, the catalyst beds in all of the runs made in the general parametric study are of unequal weight. Thus, in Run 8, the first, second, and third bed weights were 17, 19, and 23 lbs, respectively. In practice, it would be desirable for all beds to be the same size, for ready interchangeability, minimum inventory, etc. In Run 9, therefore, equal-sized beds (20 lbs each) were assumed. The results in Table III indicate that this change had very little effect on overall conversion, reduced the pressure drop, and introduced an appreciable imbalance in the temperature rise among the

beds. It would undoubtedly be possible to reduce this imbalance, if desired, by adjusting the air flow split to feed less bleed air to the first bed.

Under actual flight conditions, the ballast gas demand will vary over a wide range. Maximum normal demand will occur during powered descent. For the B-1 bomber, this demand has been estimated at 80 lbs/min, and is taken as the "design flow" for the reactor. To simplify the "turn-down" problem, it has been assumed that the reactor will operate in only two modes: a high-flow mode (80 lbs/min for powered descent), and a low-flow mode (8 lbs/min). During all normal operation other than powered descent (ascent, cruise, etc.), ballast gas demand will be less than 8 lb/min, and the excess will be vented.

Runs 12 and 13 were made to determine the effect of operating the system at a ballast gas flow rate of 2 1/2 times design flow, simulating emergency descent conditions. For this condition, it was estimated by Hamilton Standard that the recycle rate would be limited by fan capacity to a value of about 0.375. The calculations for these two runs indicate that excessive temperature rise and high inlet oxygen concentrations would result, particularly for the equal-bed-weight case.

In run 22, the low-flow mode of operation was simulated, using the equal bed weights assumed for run 9. For the low-flow mode, a recycle ratio of about 0.9 was determined based on the turndown limitations of the fan. Because of this high recycle rate, the calculation for run 22 assumes that all of the bleed air would be fed to the first reaction segment. The results indicate an overall conversion level of 100%, with most of the reaction occurring in the first bed. The temperature rise in that bed would be relatively low, so that minimum cooling of the recycle gases would be required. If the first bed were operated at about 100°F below the maximum allowable catalyst temperature (approximately 1337°F), no cooling between beds should be required.

Run 19 was made to estimate the effects of catalyst deactivation. The beds were sized as in run 8 for a reaction rate constant of 194,000 hr^{-1}, but the calculations assume that catalyst activity has declined to a level corresponding to a rate constant of 150,000 hr^{-1}. The results indicate the overall conversion would decrease only to 80%, with correspondingly modest increases in both inlet and exit oxygen concentrations.

5.2.4 Design Alternatives

The computer runs made for this study by no means exhaust the possible combinations of all the design parameters. They do serve to define the general effects of the more important variables, however, and show how they may be manipulated to accommodate system limitations such as maximum bed temperature, pressure drop, etc. Further exploration of the effects of the distribution of bleed air and conversion among beds would probably be desirable in an optimization study, but would not drastically change the picture as shown in this analysis.

One alternative to the three-bed series configuration (represented by run 8 or 9) which appears worthy of further consideration, is the single-bed reactor with recycle. Such a system would have several potential advantages over the series-bed arrangement. Control of the reaction should be simpler than in the series-bed situation where all beds interact with one another. The number of heat exchangers would be reduced and could probably be sized more efficiently, and with smaller pressure drop. The single-bed reactor could also be operated at close to the stoichiometric fuel/air ratio, thus minimizing the potential coking problem of the series-bed reactor operating with split-air.

The principal disadvantage of the single-bed concept is the large catalyst cross-section required. As shown for run 21, Table II, the area required for a single 1-inch thick bed would be about 17 ft^2. Pressure drop was only 0.35 psi, however. If one assumes that a somewhat higher pressure drop would be allowable for the single bed system than for the series-bed (less pressure loss in auxiliary equipment), and that improvements in the catalyst are possible (use of larger particle size without loss of activity), an increase in bed thickness to 2" with a corresponding 50% decrease in bed area appears feasible. Breaking the single bed up into a number of smaller beds operating in parallel might simplify the configuration from a mechanical standpoint and ease the problem of obtaining uniform distribution of gases over the catalyst surface.

Another possible feature which might be considered in connection with the series bed reactor is the addition of a "clean-up" bed following the three principal reactor beds. This bed could be operated at low space-velocity with no further addition of oxygen, and would serve to complete the oxidation of excess fuel and partial combustion products in the reactor exit gas when operating at design flow, should this appear desirable.

5.2.5 <u>Catalytic Bed</u>

The catalytic bed shown in Figure 5, has been made in a cylindrical configuration with a large flow area entering to enhance uniform flow distribution through it. The cylindrical configuration also allows the reactor heat exchanger headers to be made as cylindrical pressure vessels.

The catalyst is manufactured in the form of small pellets about 0.06 inches in diameter and 0.12 inches long. To hold these pellets, a sheet metal and screen frame is used. A 20x20 mesh screen is used to contain the pellets and a 3x3 mesh screen is used for structural support of the cylinder. A sheet metal dome closes one end of the cylinder and is provided with a 14.0 inch diameter flange for installation and mounting support. This dome may be unbolted from the cylindrical screen so that the catalytic pellets can be periodically replaced. In the cylindrical frame near the dome, several Belleville type springs are used to load the pellets and to compensate for any settling.

This catalytic bed is used in all three reactor heat exchangers and is interchangeable from one to another.

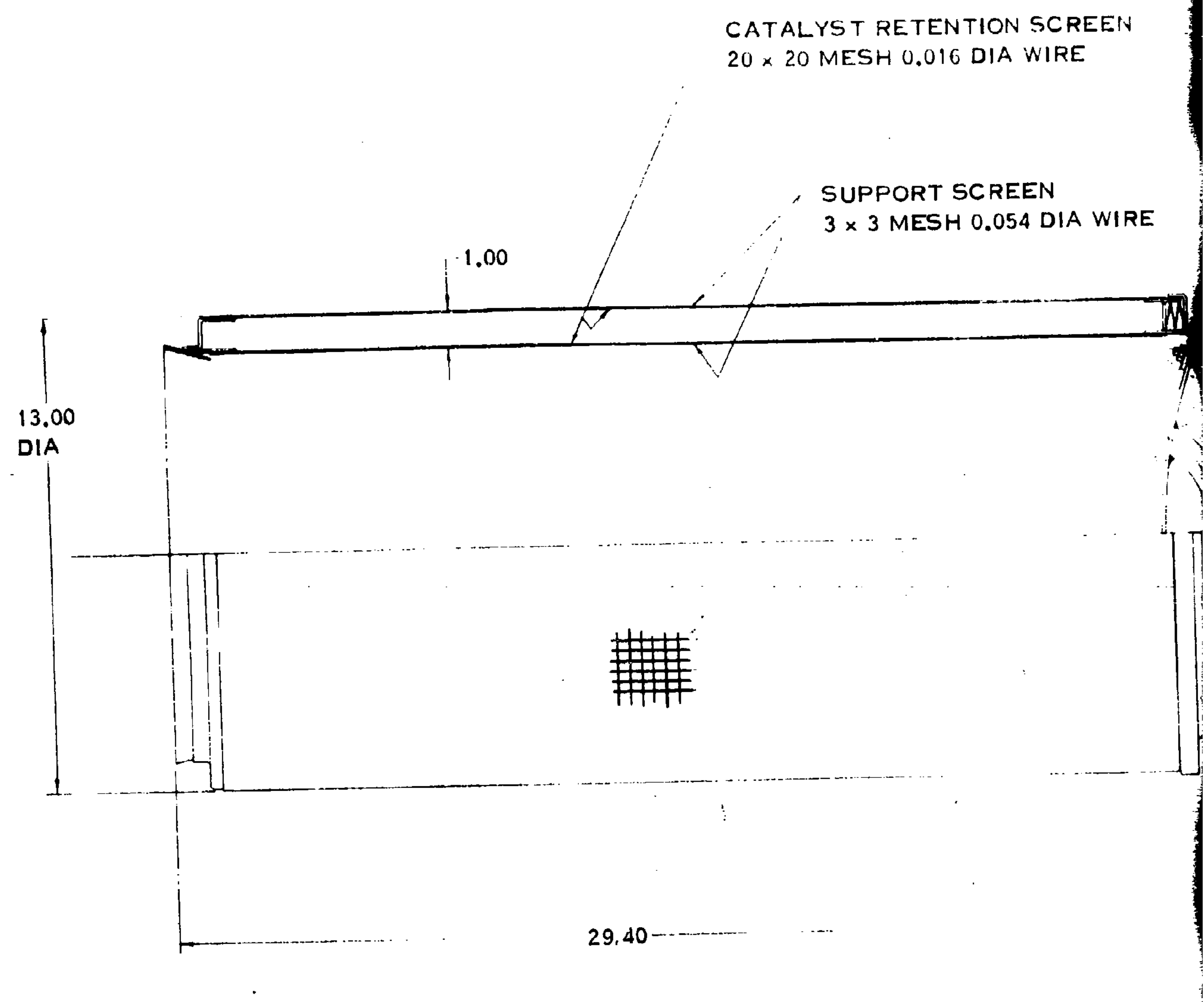
5.3 <u>Heat Exchanger, Reactor (No 1 & 2)</u>

The first and second Reactor Heat Exchangers are identical units and are shown in Figure 6. The heat exchanger core is of plate and fin design and is fabricated of Incoloy 800. The products of combustion exiting from the catalytic bed and ram cooling air each make a single pass through the core. The core dimensions are as follows:

Hot flow length = 7.36 inches
Cold flow length = 12.19 inches
No flow length = 24.68 inches

The hot side inlet header is a partial cylindrical pressure vessel shell welded to the core. A 14.0 inch diameter flange is provided for installation of the catalytic bed. Recirculated gas with fuel added enters through a 2.0 inch diameter flange. The gas leaving the heat exchanger core exits through an 11.0 inch diameter flange.

The ram cooling air enters the core through a rectangular "picture frame" type flange and exits through a sheet metal header with an 8.0 inch diameter flange.



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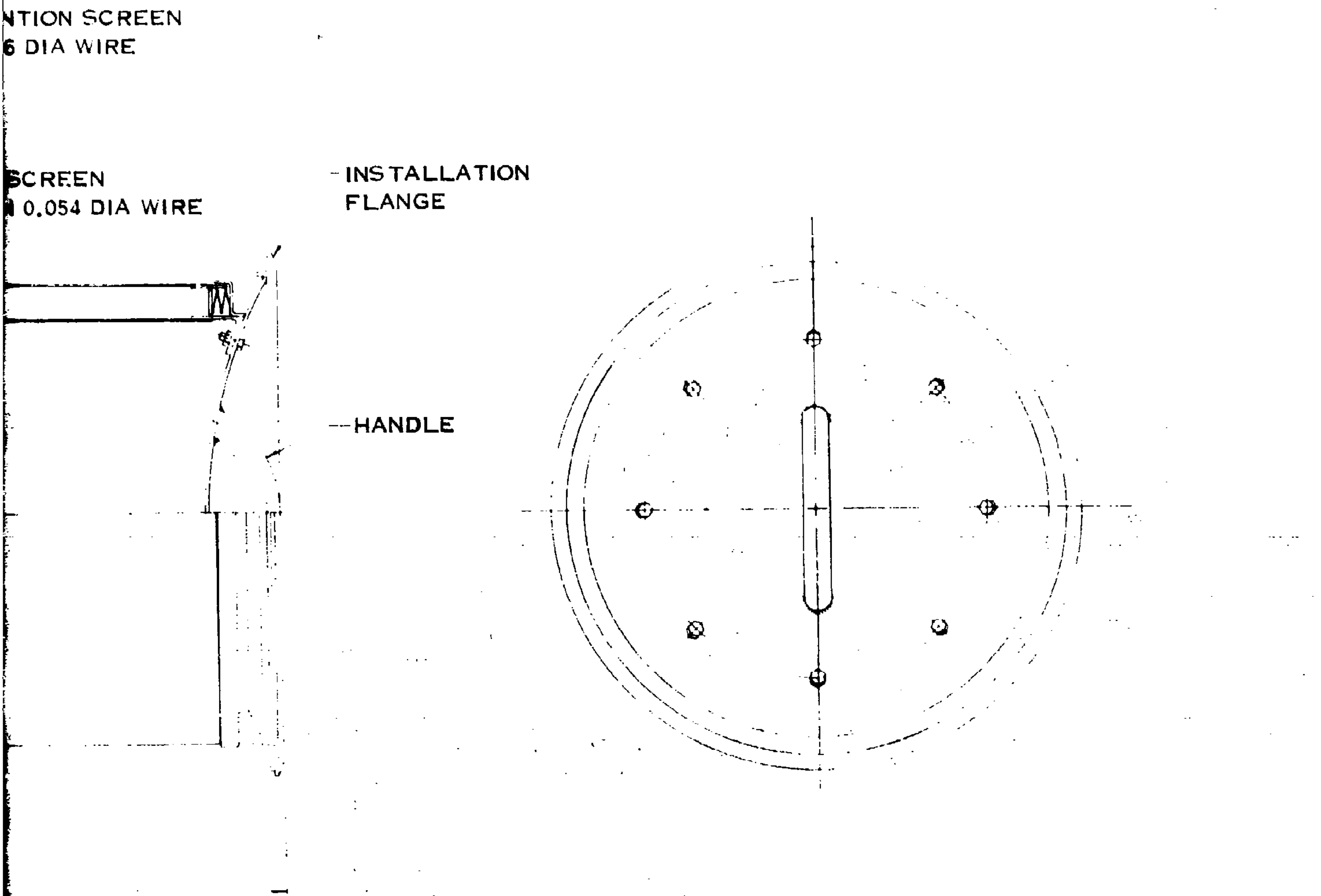
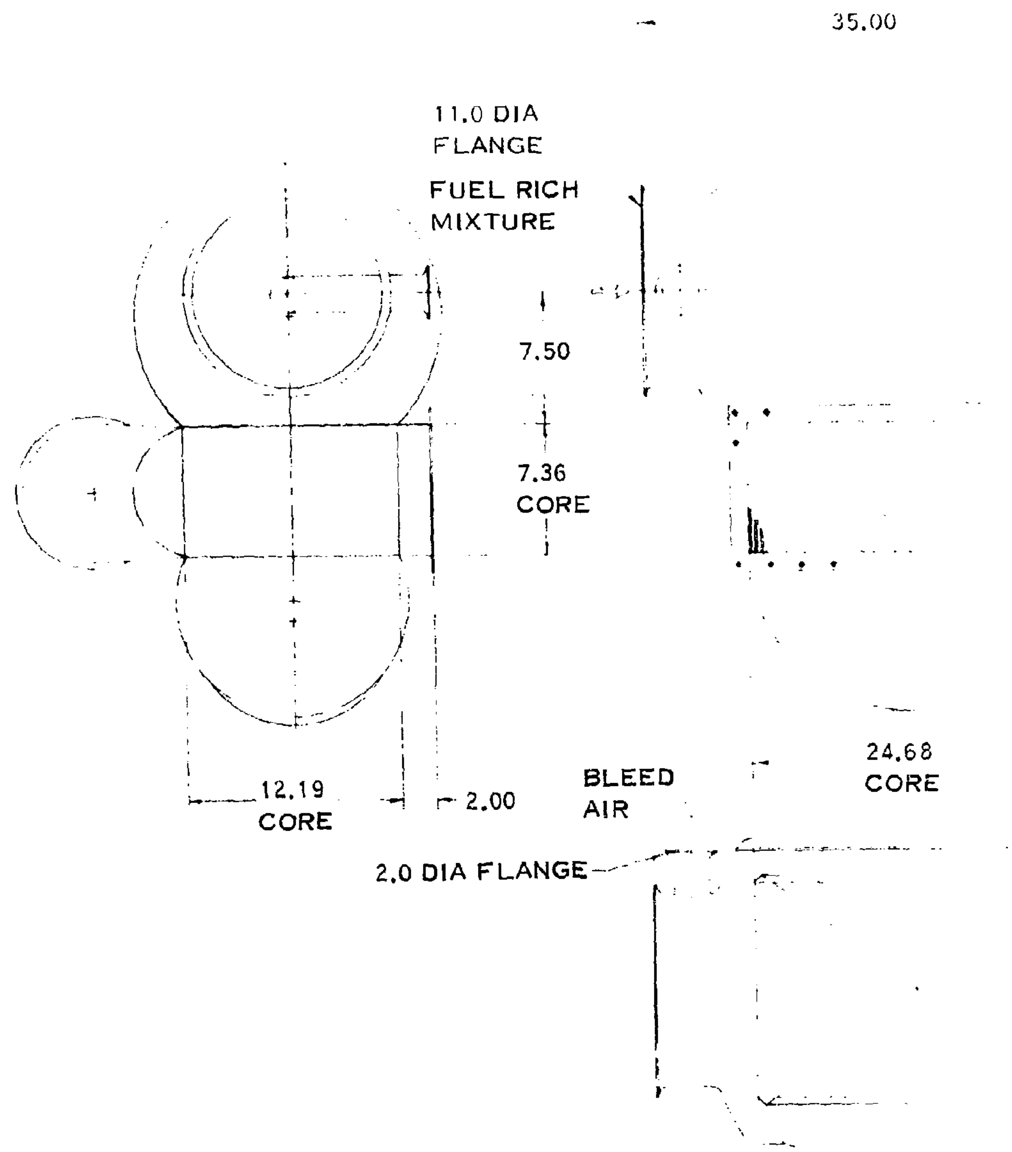


FIGURE 5. CATALYTIC BED



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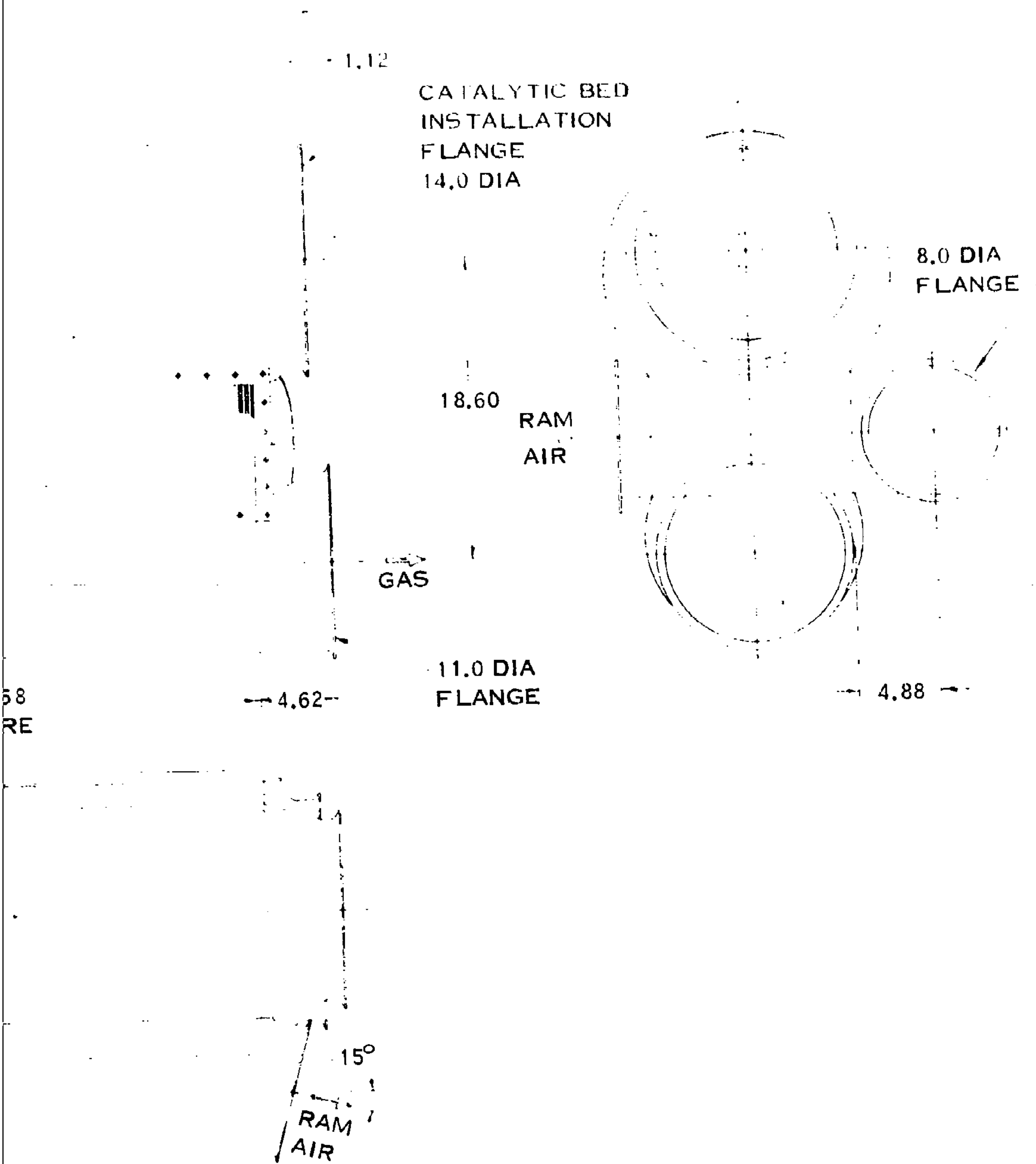

FIGURE 6. REACTOR NO. 1 & 2
HEAT EXCHANGER

2

The hot gas outlet and ram air outlet locations may be modified significantly if required to meet the installation space envelope available. Heat exchanger mounting provisions (not shown on drawing) are dependent upon the installation position of the unit, however, mounts may be welded to the two end-sheets of the core.

5.4 Heat Exchanger, Reactor (No. 3)

The third Reactor Heat Exchanger is similar in design to Reactor Heat Exchangers 1 & 2 except that it has a larger core in order to reduce the hot gas temperature to a lower level. It is shown in Figure 7. The core dimensions are as follows:

Hot flow length = 13.63 inches
Cold flow length = 10.87 inches
No flow length = 25.26 inches

The header arrangement is similar to Reactor Heat Exchangers 1 & 2 except that the ram cooling air exit flange is 10.0 inches in diameter.

5.5 Assembly of Reactor Heat Exchanger and Catalytic Bed

The catalytic bed is designed to slide into the Reactor Heat Exchanger hot gas inlet header through the 14.0 inch diameter installation flange and is held in place by a "V" band-type coupling at the insertion end and a slip fit on the gas inlet end of the header. This arrangement allows the catalytic bed to be replaced periodically without dismantling the three reactor heat exchangers or their associated ducting. This design feature, which permits quick removal of the catalyst for regeneration or replacement, was considered as an essential feature of the design. At this point in the program too little is known about the ultimate life of the catalyst. It has been added even though operation procedures have been established which will supposedly regenerate the catalyst during normal shut-down operation. If more extensive operational data on the catalyst shows that frequent replacement is unnecessary, this feature can be eliminated with a corresponding weight reduction.

Recirculated gas mixed with fuel enters the header through an 11.0 inch diameter inlet. Bleed air enters through a 2.0 inch diameter duct. Inside the header this duct is perforated to allow the bleed air to mix with the fuel/gas mixture. This mixture then flows radially through the catalytic bed where the oxygen in the bleed air reacts with the fuel. Hot gas leaving the catalytic bed enters the core of the heat exchanger where it is cooled by ram air. This process is repeated three times in the

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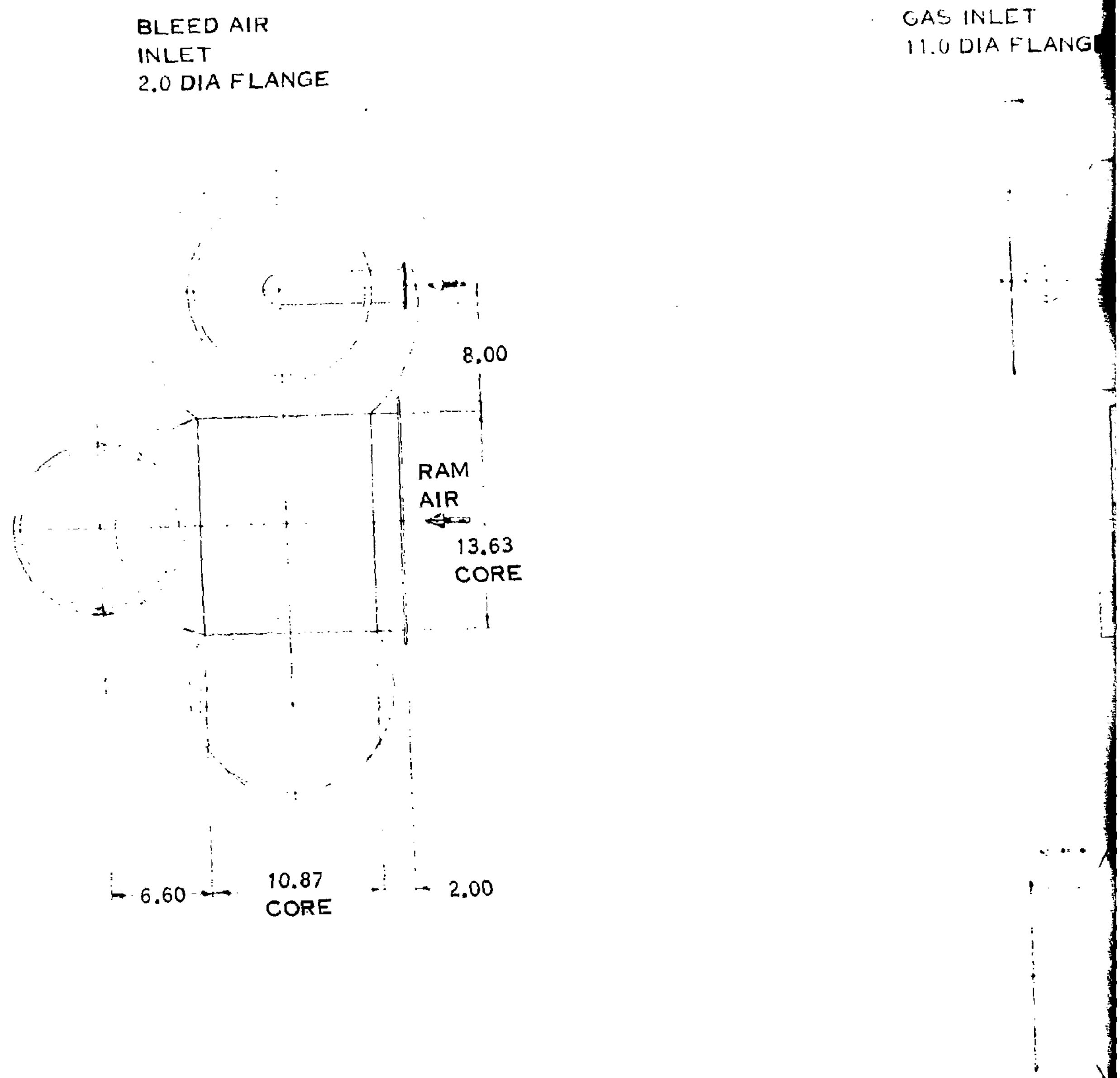

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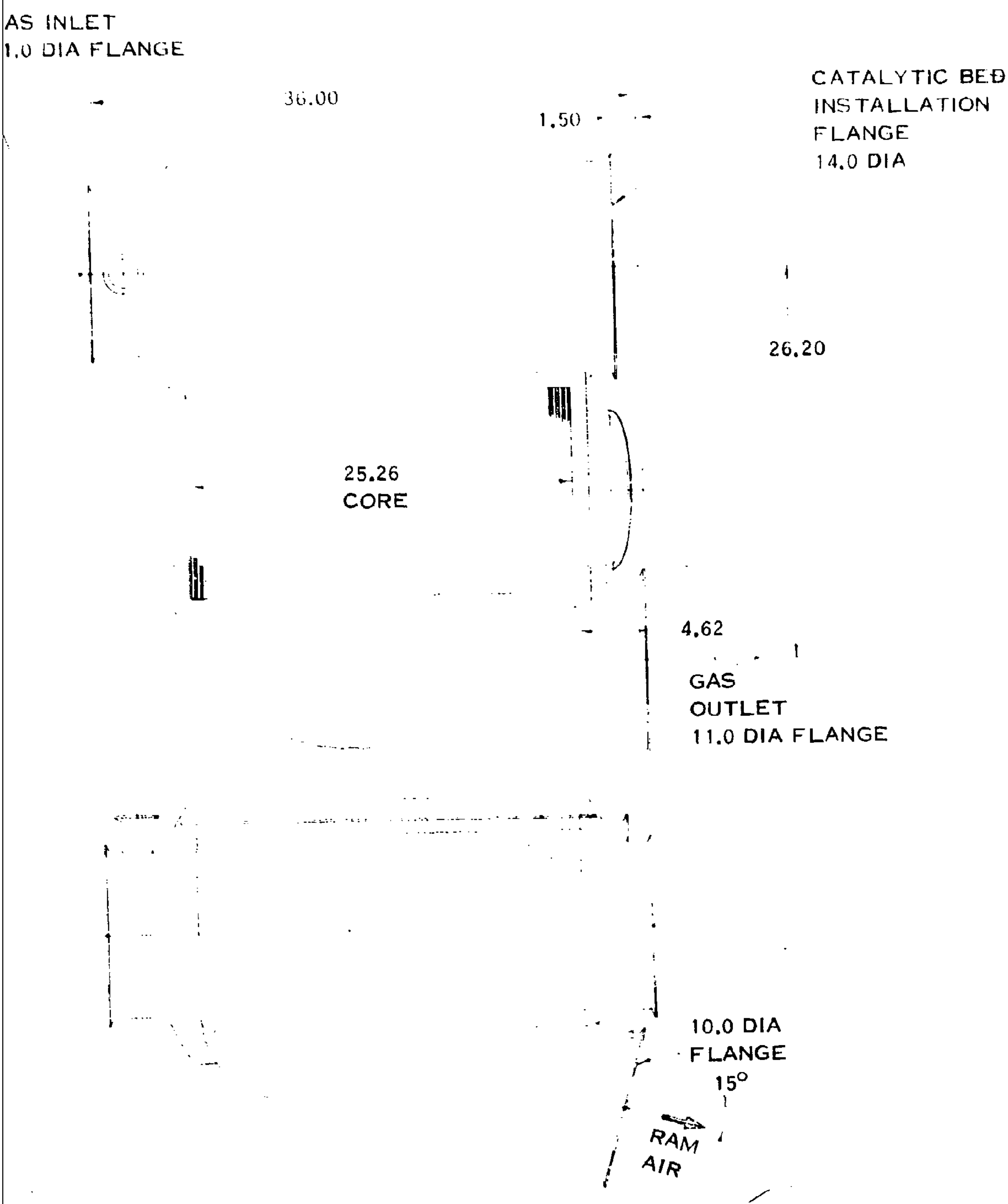

FIGURE 7. REACTOR NO. 3
HEAT EXCHANGER

reactor portion of the system. Figure 8 shows the assembly.

5.6 Fuel Injector, Nozzles & Shut-Off Valves

The fuel injector consists of a 4.0 inch diameter duct formed into a venturi shape which acts as a mixing section for the fuel-gas mixture. Two solenoid valves and two spray nozzles control the fuel flow into the venturi. The valves are on-off type which give a selection of low fuel flow (0.7 lb/min) or high fuel flow (0.57 lb/min). The valves act only as a means of switching flow, Figure 9 gives details of components. The flow rate is controlled by an orifice in each spray nozzle, one nozzle operates during the low-flow condition and both nozzles operate for the high-flow rate. The fuel supply pressure will have to be specified by the customer so that the nozzle orifices may be properly sized.

In both the high- and low-flow modes, the fuel entering the valves passes through both solenoids and provides cooling. The valves are coaxial in design and compactness is achieved by having the solenoid plunger carry the valve poppet seal. The valves are designed to operate at temperatures ranging from -65°F to +450°F. The following is a tabulation of electrical data.

Voltage - 18 to 30 volts DC
Duty - continuous
Dielectric Strength - 1000 volts RMS minimum
Current Draw - 1.5 amps max to 30 VDC and 70°F for each solenoid

5.7 Heat Exchanger, Precooler

The precooler is a plate and fin type design fabricated of Incoloy 800 material as shown in Figure 10. Inerted gas flow makes two passes through the core while ram cooling air makes a single pass. The core dimensions are as follows:

Hot flow length = 18.10 inches
Cold flow length = 11.90 inches
No flow length = 29.97 inches

Inerted gas enters and leaves the unit through 4.0 inch diameter flanges. A water collector is provided on the outlet duct to collect water which condenses in the core.

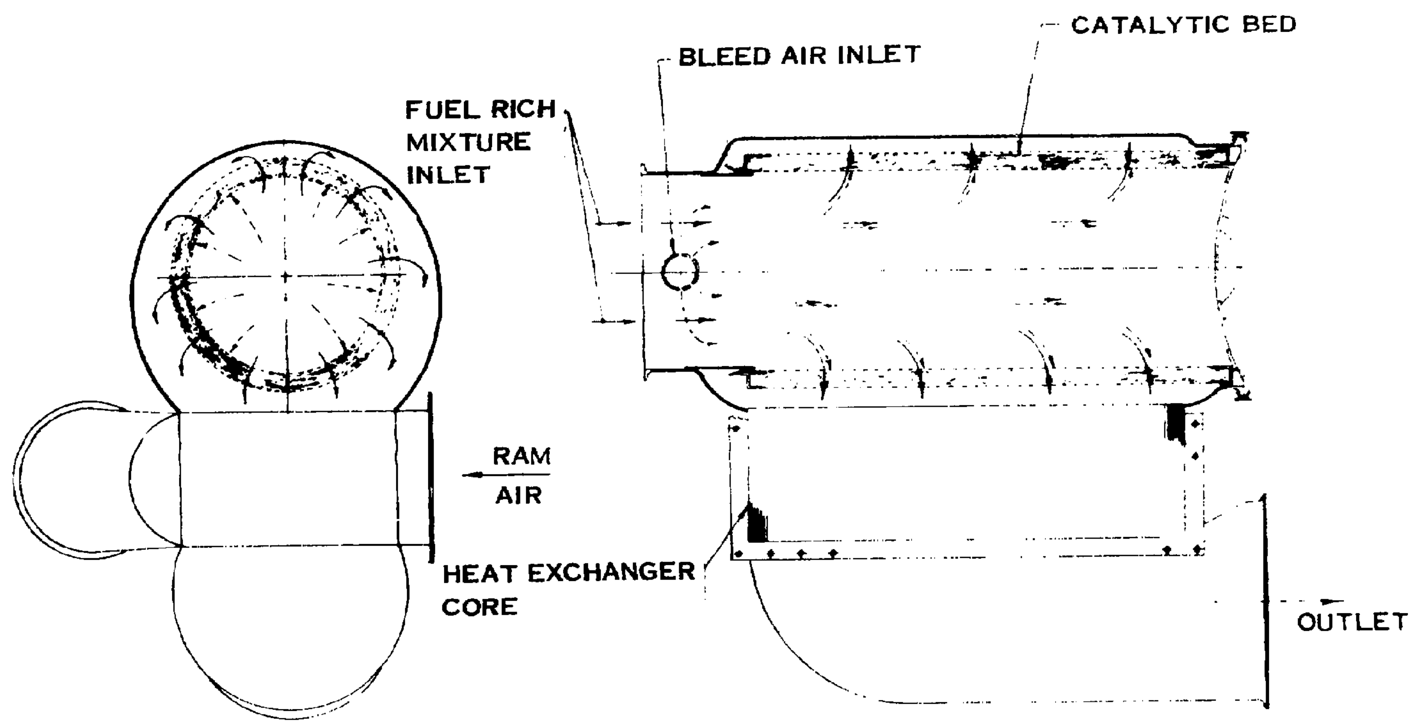

FIGURE 8. CATALYTIC BED & HEAT EXCHANGER
(REACTOR NO. 1 & 2) ASSEMBLY

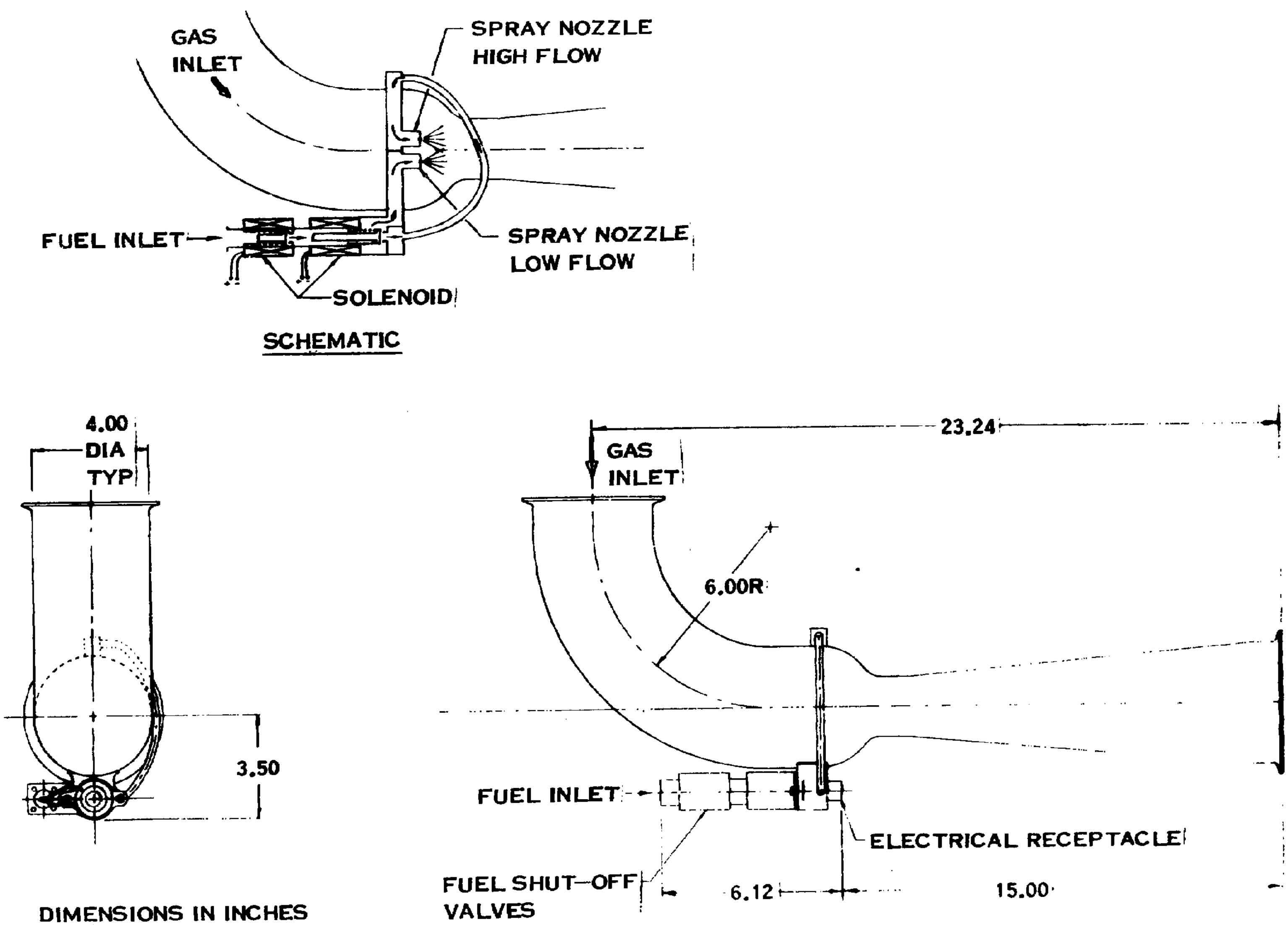

FIGURE 9. NOZZLES & SHUTOFF VALVE FUEL INJECTOR

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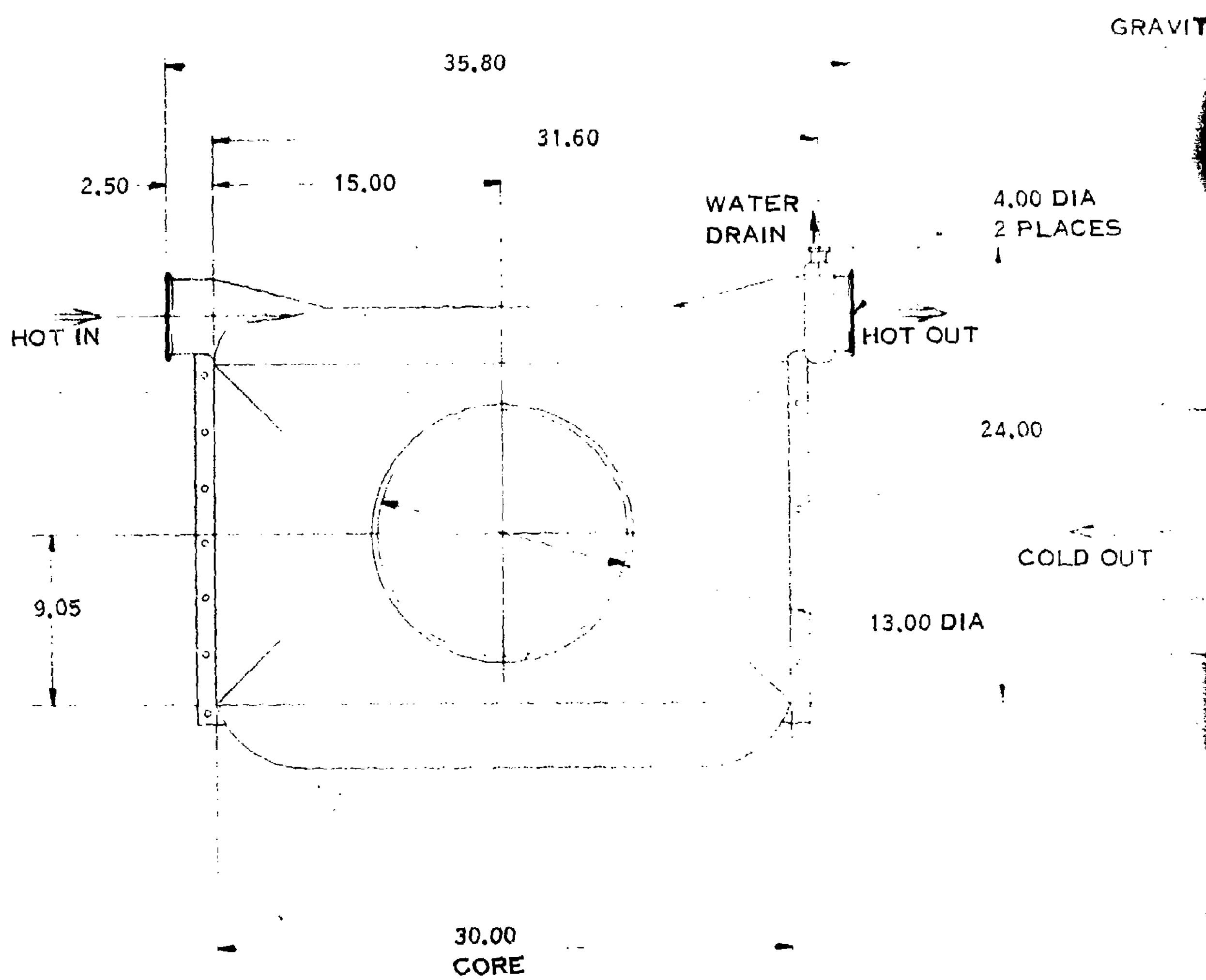

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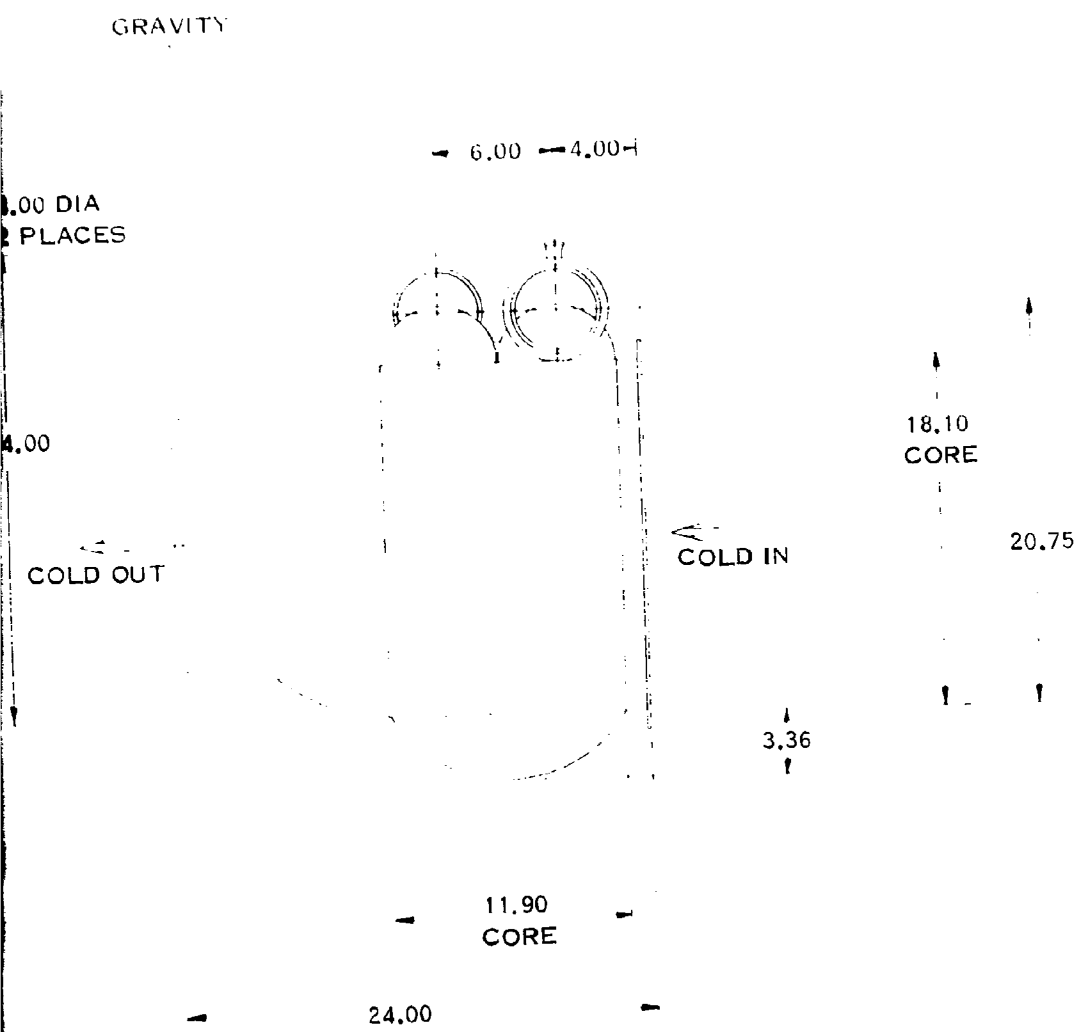

FIGURE 10. PRECOOLER

The water collected at the precooler and other downstream heat exchanger outlets is sprayed into the ram cooling air duct upstream of the precooler. This flow enters the precooler through a rectangular "picture frame" style flange. The ram air exits through a 13.0 inch diameter flange.

5.8 Heat Exchanger, Fuel

The fuel heat exchanger is a plate and fin type, cross-counterflow design fabricated of Incoloy 800 material and is shown in Figure 11. Fuel makes four passes and the inerted gas makes a single pass through the core. The core dimensions are as follows:

Hot flow (gas) length = 7.55 inches
Cold flow (fuel) length = 6.61 inches
No flow length = 7.28 inches

Fuel enters and leaves the unit through 1.50 inch diameter flanges. The inerted gas enters and exits through 4.0 inch diameter flanges. The gas outlet header contains a water collector and drain boss for collecting water vapor which condenses out in the heat exchanger core.

5.9 Heat Exchanger, Regenerative

The regenerative heat exchanger is of plate and fin type construction and fabricated of Incoloy 800, and shown on Figure 12. The operating temperatures of this unit are quite low (about 150°F max) and it is made of Incoloy only to resist the corrosive acids which are present. The inerted gas and the turbine discharge gas each make a single pass through the core. The core dimensions are as follows:

Hot flow length = 9.81 inches
Cold flow length = 15.20 inches
No flow length = 12.16 inches

The hot-side inerted gas enters and exits through 4.0 inch diameter flanges. A scupper type water collector and drain is incorporated into the outlet header to collect condensed water. The cold-side gas enters and leaves through 5.0 inch diameter flanges.

5.10 Heat Exchanger, Bypass Regenerative

The bypass regenerative heat exchanger is a plate and fin style unit made of Incoloy 800 material, and shown in Figure 13. This heat exchanger has

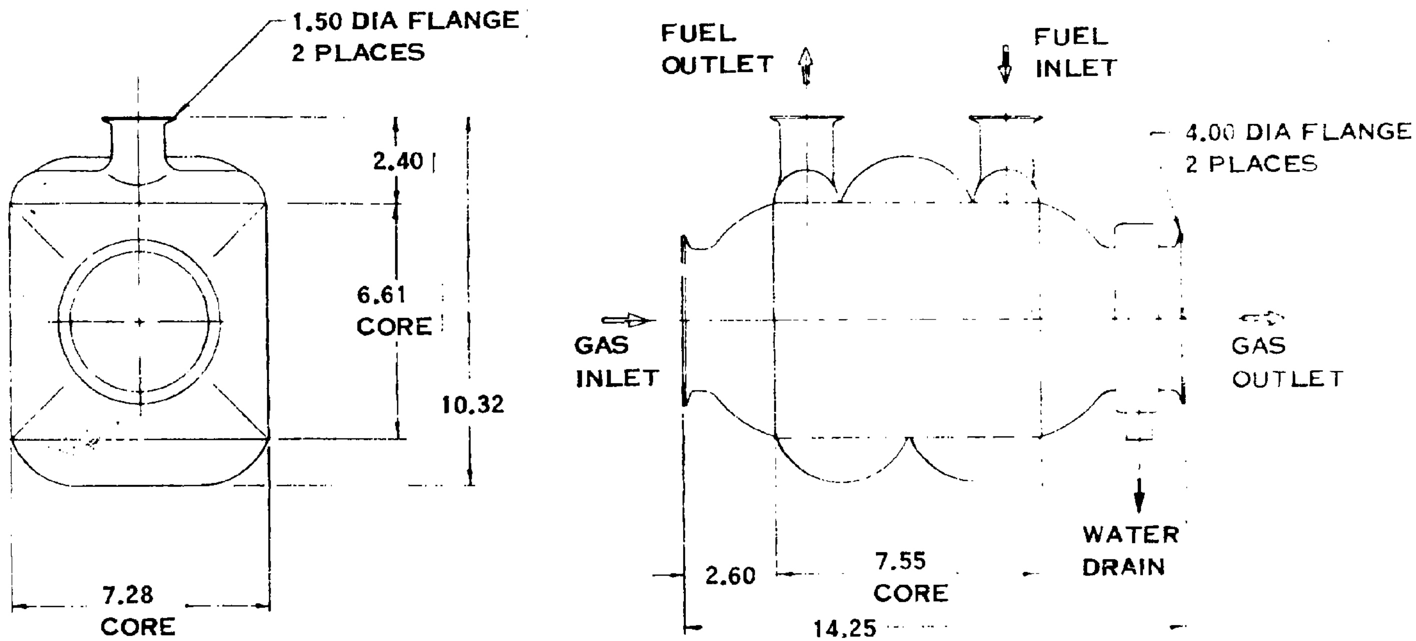

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FIGURE 11. GAS-TO-FUEL HEAT EXCHANGER

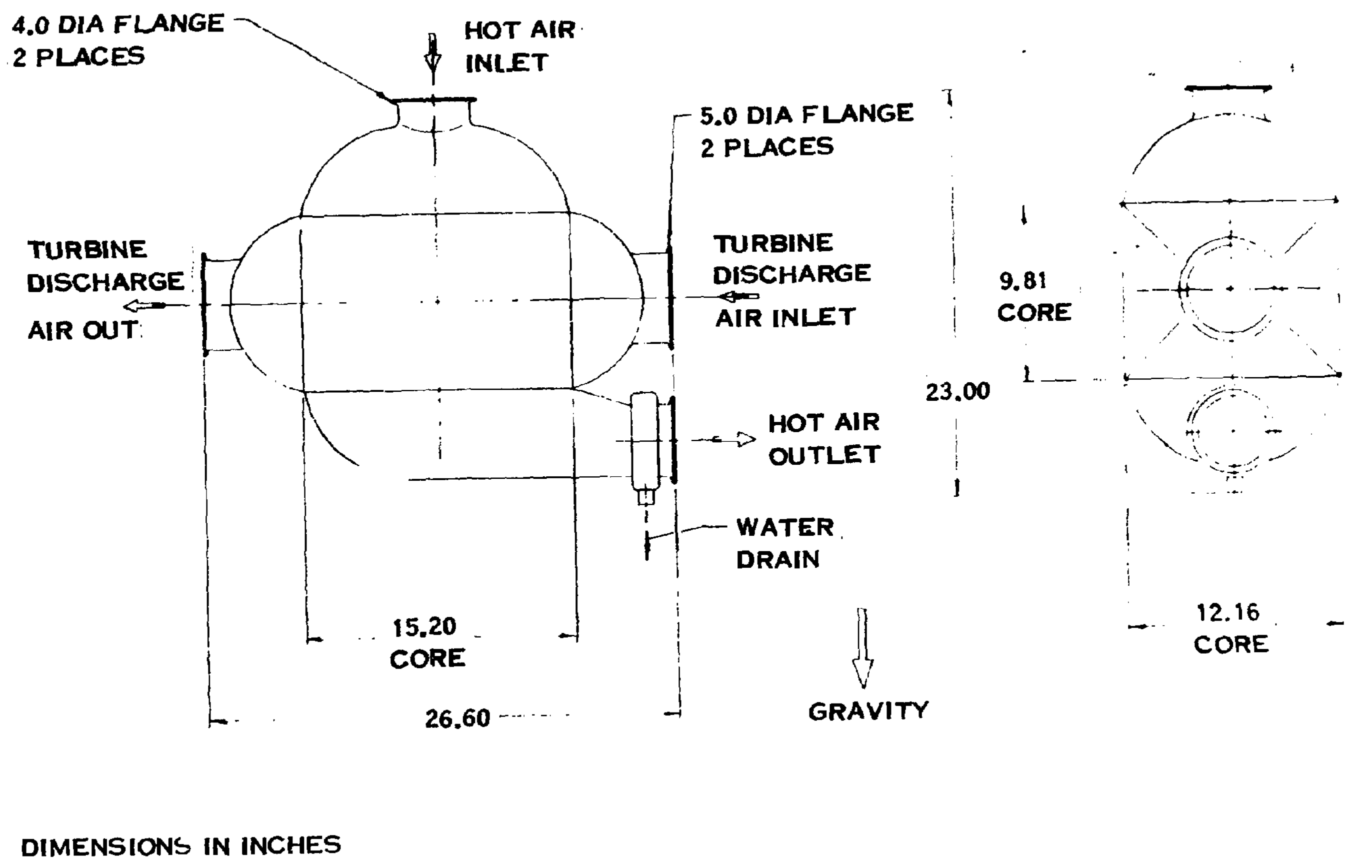

FIGURE 12. REGENERATIVE HEAT EXCHANGER

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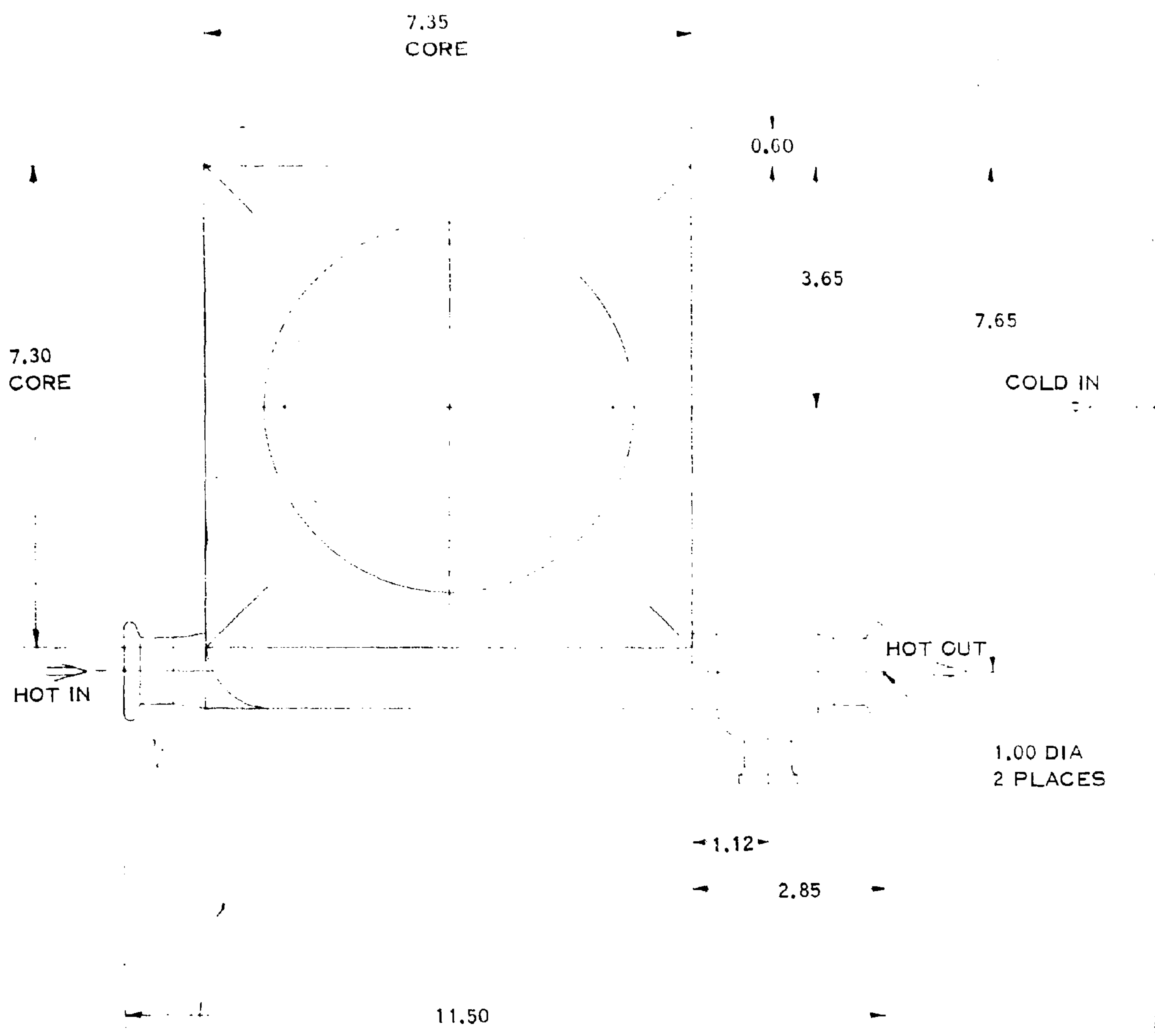

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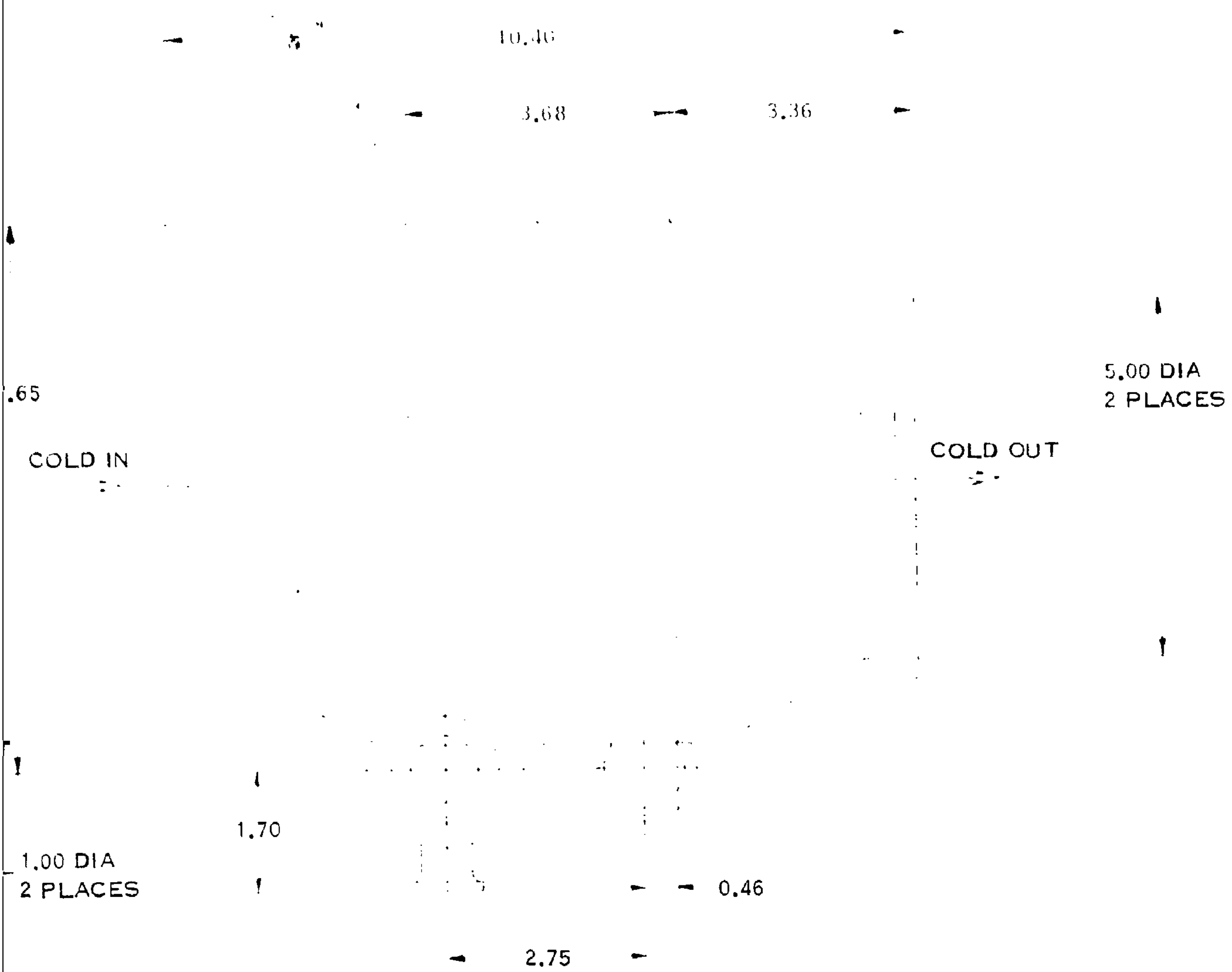

FIGURE 13. BY PASS REGENERATIVE
HEAT EXCHANGER

very low operating temperatures (about 150°F max) and is fabricated of Incoloy only because of the corrosive acids which collect in the core. The hot-side inerted gas makes four passes through the core and the cold-side gas makes a single pass. The core size is as follows:

Hot flow length = 7.30 inches
Cold flow length = 3.68 inches
No flow length = 7.35 inches

Hot inerted gas enters and exits the unit through 1.00 inch diameter flanges. A scupper type water separator and drain are provided on the outlet header to collect condensed water. The cold gas flow enters and leaves the core through 5.0 inch diameter flanges.

5.11 Ejectors (Cooling Air)

For ground static operation, or when ram pressure is inadequate, ejectors are used to provide cooling air for the reactor heat exchangers. One ejector provides cooling air for all three reactor heat exchangers and another ejector is used to draw cooling air through the precooler; these are shown on Figure 14.

The ejector is of welded construction and consists of an outer housing with V-band flanges. A 2.0 inch diameter bleed air inlet tube with a V-band type flange passes through the outer housing. Seven nozzles are attached to the tube. Air exits through the nozzles at a high velocity, creating a low static pressure region that induces a flow of cooling air through the heat exchangers.

The outer housing diameters are 13.0 inches for the procooler ejector and 15.0 inches for the reactor ejector.

5.12 Turbine/Fan

The proposed turbine/fan unit features Hamilton Standard's patented single-ended design, with a radial flow turbine and mixed flow fan. Both rotors are unshrouded.

Several distinct advantages result from the single-ended concept.

a. The bearing cartridge is cooled by turbine exhaust air, thus eliminating problems associated with high temperature lubrication.

PART NO.	A DIM	B DIM	FOR
−1	15.00	9.50	REACTOR
−2	13.00	8.50	PRECOOLER

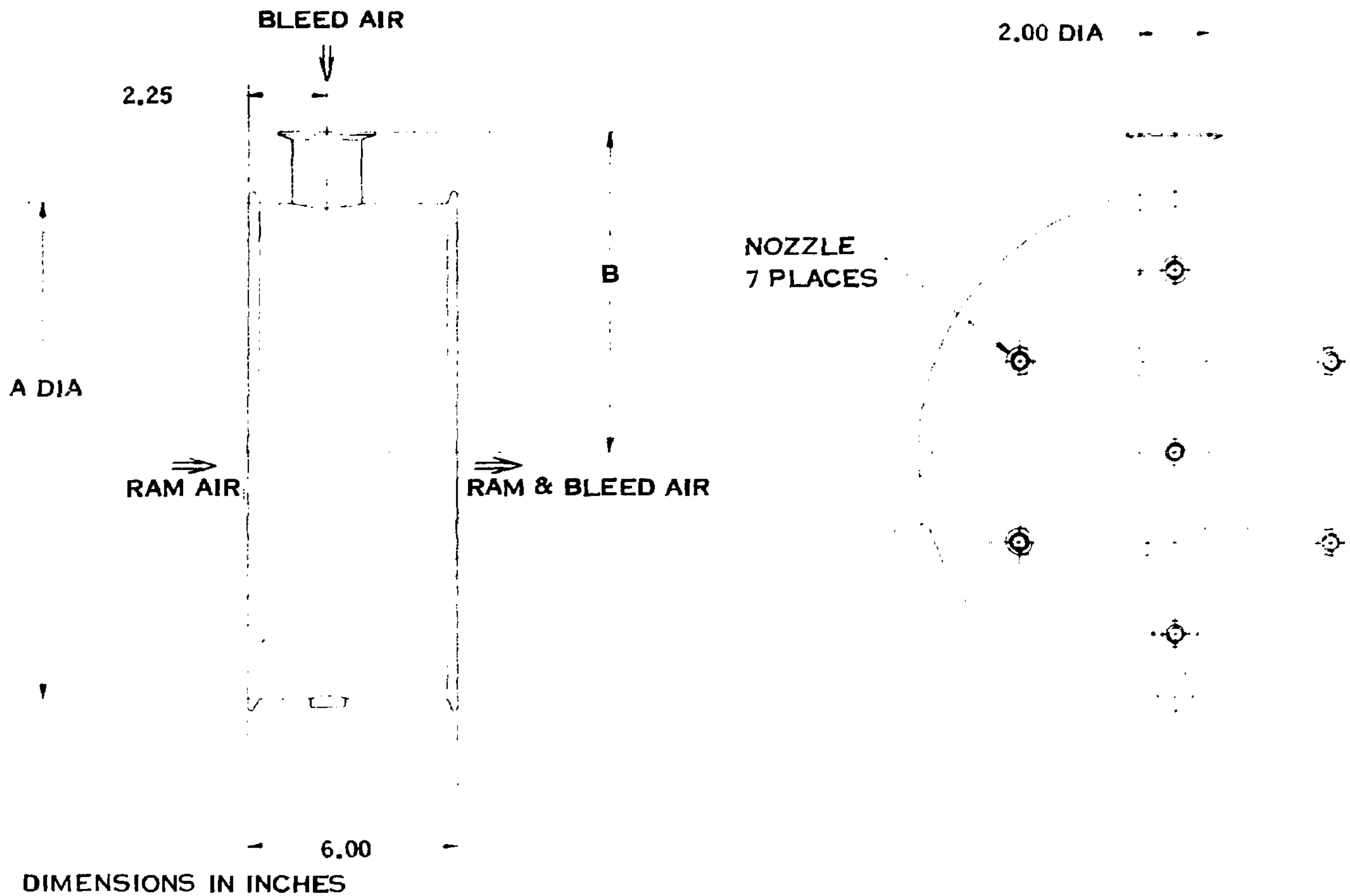

FIGURE 14. RAM AIR EJECTOR

b. One end of the bearing cartridge is sealed statically, thereby eliminating leakage or air circulation through the bearing assembly.

c. Only one rotating seal is required.

d. The entire rotating assembly may be dynamically balanced without the parasitic mass of the turbine housing. This allows a more sensitive balance and contributes to smoother operations.

Details of the assembly are given on Figure 15.

Turbine Fan Characteristics

Rotors

The turbine is a two-piece, radial flow rotor, fused to limit maximum burst speed. Two-piece construction provides blade damping, thereby minimizing vibratory blade stresses. Turbine diameter is 4.71 inches.

The fan is a one-piece rotor with a tip diameter of 4.74 inches.

Both rotors are machined from 6A1-4V titanium forgings which provide high material properties and good corrosion resistance.

Housings

The cast Inconel turbine housing provides external support for the unit and also supports the bearing cartridge. Two separate turbine inlets, with a 90% and 10% area split, provide dual nozzle capability. During steady flight conditions, the smaller inlet directs flow into 2 of the 19 nozzle passages and allows operation with low weight flow. Use of the two inlets supplies all 19 nozzle passages with flow. This enables the system to respond to rapid changes in ambient pressure (as in a rapid descent), and maintains a positive pressure in the aircraft fuel tanks.

The fan housing material is Inconel 625 and is of welded construction.

Nozzle

The nozzle contains 19 passages and forms one wall of the turbine housing. In addition, it supports a silver labyrinth seal which

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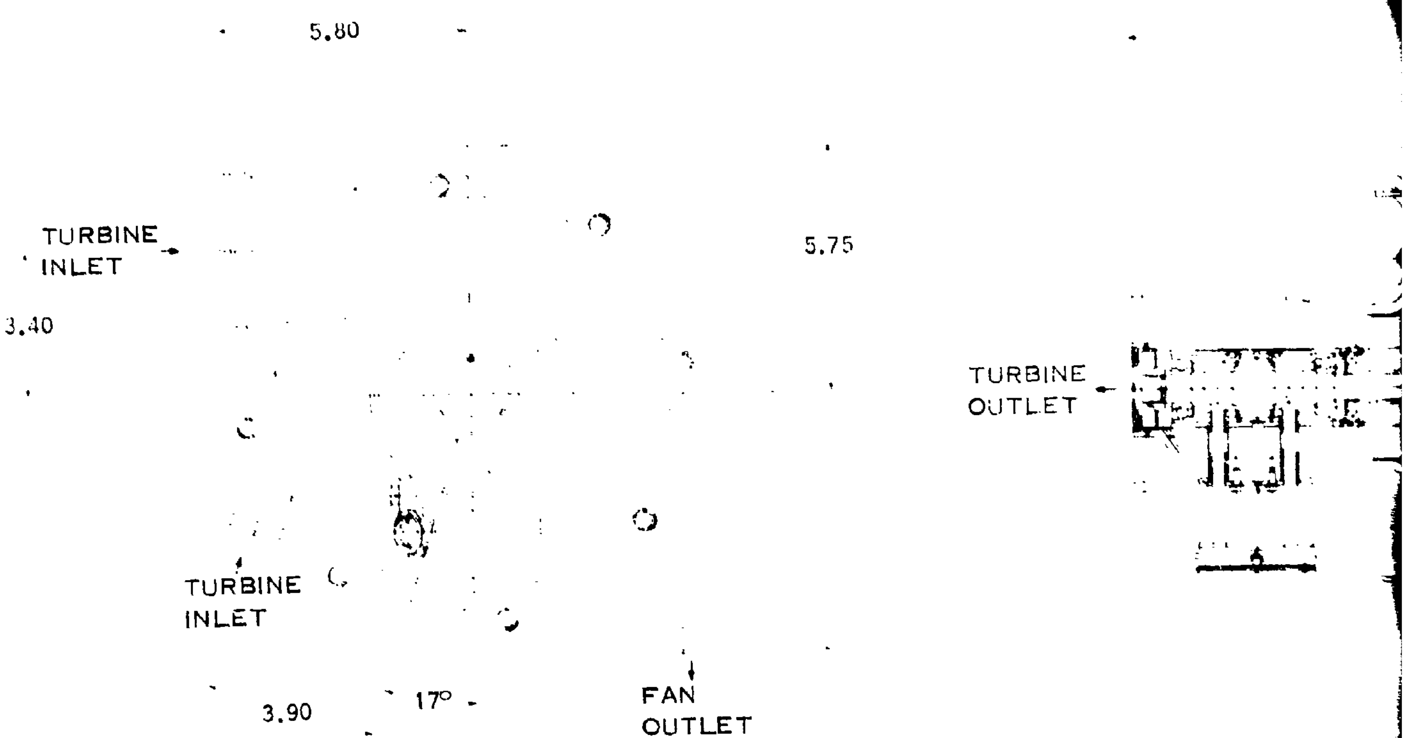

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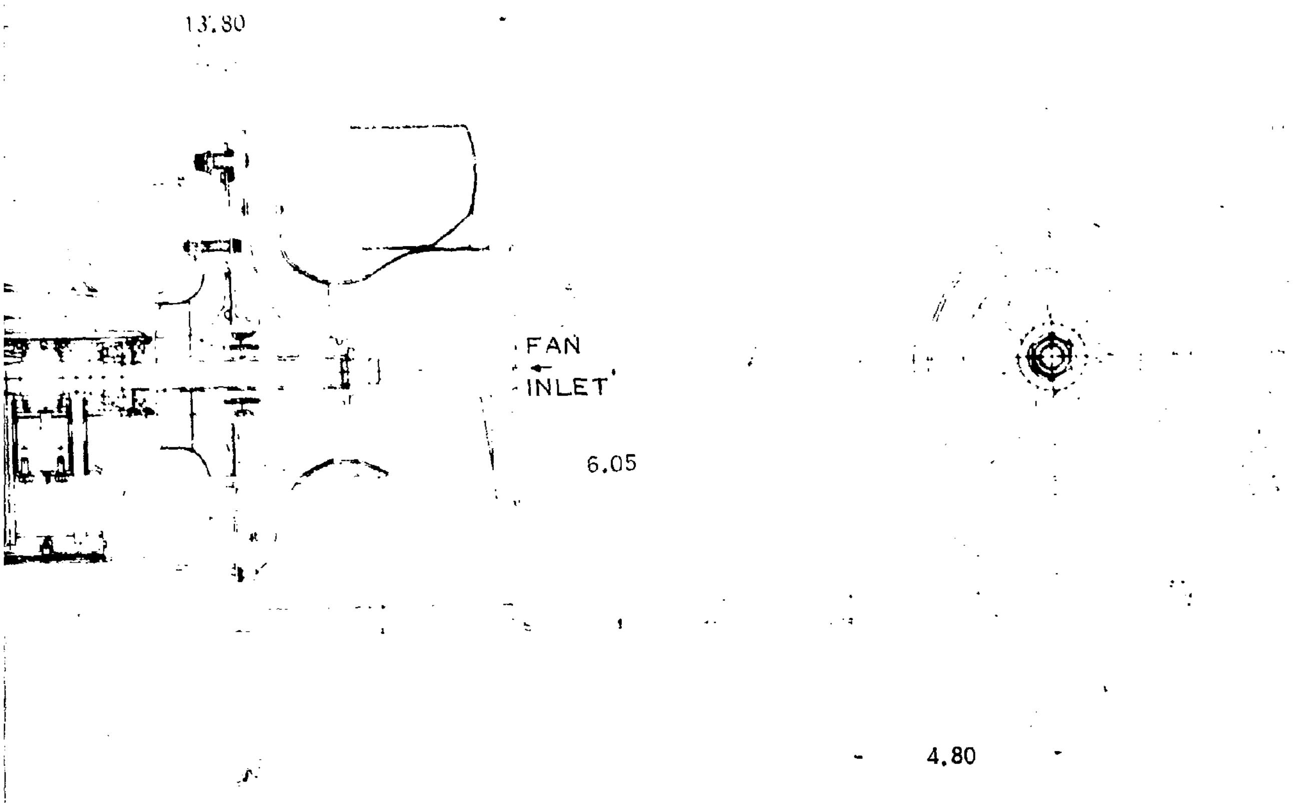


FIGURE 15. TURBINE/FAN FUEL TANK
INERTING SYSTEM

2

isolates the turbine and fan circuits. The nozzle plate is a Stellite 31 investment casting. Critical dimensions, such as nozzle throats, are machined.

Lubrication

Lubrication of the two bearings is provided by two felt wicks which direct oil from the sump to the shaft. As the oil is deposited on the shaft, centrifugal forces sling the oil to the inner walls of the spring seats. It then collects in oil grooves in the spring seats and is fed to the bearing outer race. After passing through the bearings, the oil drains into the sump to be recirculated. The oil reservoir contains approximately 125 cc of oil, which has been found to be adequate for operation in excess of 1,000 hours.

Rotor Containment

The turbine houcing provides containment for a turbine fuse burst and for a tri-hub burst. Fan housing provides containment for fan blades and for a fan tri-hub burst. Both rotors are contained at 135% of maximum normal speed or at the maximum speed that can result from any single failure-inducing condition. The turbine is fused to burst at a lower speed than the fan. This approach assures that the driving member will burst before the driven member, thus resulting in lower containment weight.

Bearing Cartridge

The bearing cartridge is located downstream of the turbine and is surrounded by cool turbine discharge gas. A carbon face seal isolates inert gas products which might contain corrosive elements from the cartridge environment. All other ports are sealed statically. Two spring-preloaded, angular contact ball bearings support the rotor shaft. The bearings sleeve is a steel tube which is free to move radially within the turbine housing. Damping of the rotor shaft system is accomplished by a flexible, oil-film-damped rotor suspension. This consists of a predetermined diametral clearance between the bearing sleeve and the turbine housing, which is supplied with bearing lubrication oil in sufficient quantities to damp out excessive vibration due to shaft resonance. Either, or both, of the bearings may be damped depending on system dynamics. All other fits and clearances in the cartridge area are optimized to contribute to the proper amount of damping.

5.13 System Controls and Valves

5.13.1 Fuel Tank Pressure Control

The inerting system provides the prime means of controlling fuel tank to ambient differential pressure. A backup system, consisting of a relief valve and a dive valve, provide protection from overpressure and negative pressure, respectively. The specified pressurization schedule calls for maintenance of 0.5 psig or 6.0 psia, whichever is greater. This indicates constant fuel tank pressure above 25,000 ft.

The fuel tank pressure control involves controlling the gas flow to the tanks according to the actual demand, as sensed by an underpressure condition. The excess flow is passed overboard through the overboard spill valve, rather than through the fuel tank. This approach minimizes the addition of contaminants in the inert gas (water, carbon dioxide, etc.) by limiting the gas flow to the tanks to the minimum required. The control scheme involves two valves, namely the fuel tank pressure control valve (in the low flow supply line) and the excess flow overboard spill valve, and the control function is in one or the other depending upon the mode of system operation. In the normal (low-flow) mode, the gas flow to the tanks is modulated by the pressure control valve while the overboard spill valve is wide open. The check valve in the crossover line prevents flow from the tank supply line from crossing over to the overboard line.

In the high-flow mode during descent, control switches to the overboard spill valve and the pressure control valve are shut. The excess flow produced by the system is modulated overboard according to the demand for pressurization flow as signaled by an underpressure condition in the fuel tanks. In the case where the system flow just meets the demand, the overboard valve would be closed and all the flow would go to the tanks.

To implement this control scheme, fuel-tank-to-ambient-differential pressure is sensed across a diaphragm, compared to a reference delta P, and the error used to modulate the pneumatically actuated valve in control.

5.13.2 System Flow Control

Control of the inerting system throughout flow is maintained by a combination of components. The pressure regulator upstream of the turbine is provided to limit the pressure into the turbine. The setting of the regulator

is 21 psig, which assures no throttling at the idle descent condition which determined the size of the turbine nozzle. The flow-limiting venturi is provided to limit the maximum combined turbine and anti-ice bypass flow. Flow tapped off by the bypass regenerator line is controller by the modulating fuel tank pressure control valve.

5.13.3 Catalyst Bed Temperature Control

Maintenance of catalyst bed temperature is accomplished by modulating the ram air cooling flow through the heat exchanger upstream of the bed. A separate control is provided for each of the three reactor segments, thus assuring localized protection from both overheating and overcooling (quenching). The reactor temperature control is based upon controlling the temperature at the catalyst bed discharge. A normal setting of 1100°F is maintained during low-flow operating. This is switched to a setting of 1337°F (725°C) during high-flow mode when higher temperature rises across the catalyst beds are expected. The setting of 1337°F represents a maximum recommended catalyst operating temperature. In obtaining control, the catalyst-bed discharge temperature is sensed by a bimetallic temperature sensor and compared to the setpoint reference temperature. The control converts the error signal into a change of servo pressure, causing an integrating pneumatic actuator to move the control valve until the temperature error is reduced to zero. Low temperature in the catalyst bed, such as during start-up, would close the ram control valve.

5.13.4 Fuel Heat Sink Control

The use of fuel as a supplemental heat sink when the ram air temperature is high greatly improves the moisture removal capacity of the cooling system. A simple on/off fuel valve is utilized to control the flow of cooling fuel through the fuel heat exchanger. The control consists of a bimetallic temperature switch which opens the pneumatically actuated fuel valve when the sensed temperature exceeds the switch point. When the ram air temperature falls below the switch point, the valve is driven closed. The setpoint chosen for this switch is 150°F.

5.13.5 Anti-Ice Control

Anti-Ice Control

Anti-ice protection is provided by a turbine bypass line which permits mixing of warm turbine inlet gas with the cold turbine discharge in order to prevent below-freezing temperatures at the inlet to the bypass the

regenerative heat exchanger. A turbine bypass valve is provided which modulates bypass flow in response to an undertemperature condition. A mixed temperature of 35° F is the nominal set-point for this control.

In conjunction with the turbine bypass anti-ice control, a minimum temperature control is provided at the precooler discharge. This control modulates the precooler ram air control valve to hold a minimum hot-side discharge temperature of 90° F. This control function was provided in order to maintain an elevated turbine inlet temperature, thereby avoiding excessive turbine bypass flow. The control setpoint was selected after consideration of the compromise to the moisture removal capacity that would result from a higher setting. This control also serves the purpose of protecting the precooler from icing. When low ram temperatures are encountered, it is feasible to conclude that an uncontrolled ram air heat sink could result in an icing condition. This possibility is obviously eliminated by controlling the precooler discharge to 90° F.

5.13.6 Ground Operation Control

Operation of the inerting system on the ground necessitates the use of ejectors in induce ram air cooling flow. A simple on/off valve will supply the bleed flow to the ejector nozzles upon receiving a signal to open. Such a signal could be a switch which would sense pressure on the aircraft landing gear.

5.13.7 Fuel Supply Sparge Control

During climb and fueling operations, the potential exists for high release rates of oxygen dissolved in the fuel. Agitation of the fuel supply promotes the gradual release of dissolved gases. When this sparging is done with inert gases bubbled through the fuel, it is possible to dilute the oxygen concentration in the ullage space and maintain an inert ullage atmosphere.

The sparge control function of the inerting system utilizes a simple on/off valve which would open upon signal and pass flow to the sparging nozzles located under the fuel supply. The flow would first pass through the bypass regenerative heat exchanger for cooling and reduction of moisture content. The fuel tank pressure control valve would be closed since there is an over-pressure condition in the fuel tanks during operating conditions when sparging is called for.

5.13.8 Emergency Descent Pressurization

In the event of an aircraft descent at an emergency dive rate, positive pressurization is maintained by opening the emergency bypass valve and allowing bleed air to be added to the inert gas on the way to the fuel tanks. The overboard spill valve will maintain control by modulating overboard any emergency bypass flow that may be in excess of demand. A flow limiting venturi is provided in the emergency bypass line. This would be sized to pass adequate bypass flow for the worst specified emergency condition.

5.13.9 Valve and Control Design

The inerting system contains a total of fourteen pneumatically actuated butterfly valves, two hinged-flapper type check valves and three solenoid driven poppet valves for fuel-flow control. Table IV provides a listing of the system valves and controls, indicating function, size material and design weight.

The gas-handling butterfly valves are powered by either single-acting actuators, in the case of simple shutoff functions, or double-acting, half-area actuators where a modulating control function is required. The actuator pistons utilize either thin silicone rubber/dacron fabric diaphragms or teflon-filled piston rings, depending upon application. Servo pressure to drive the actuator is controlled by the associated temperature sensor, in the case of the temperature control valve, or by a pneumatic controller, in the case of pressure control valves.

Material selection for the valves and controllers was dictated by location in the system. A suitable steel was chosen for the valve bodies for both the high-temperature valves associated with the catalytic reactor and for the valves exposed to the acid condensate in the water removal and inert gas supply subsystems. Aluminum is used for the remaining valve bodies as well as for all actuator housings. In all cases, a chrome plating is applied to the valve bores for wear resistance in the sealing area. The butterfly disc and shaft assemblies are supported in the valve bodies by carbon bushings in the high-temperature valves, or teflon-lead impregnated bronze-coated steel bushings in the lower temperature applications.

A typical half area actuated butterfly valve is shown in Figure 16. The dimensions are for a 4.0 inch diameter valve.

Table IV Inerting System Valves and Controls

Valve Name and Function	Diameter inch	Valve Body Material	Design Weight lbs
Bleed Air Supply-Shutoff and Pressure Regulating	4.0	Aluminum	6.0
Ejector Bleed Supply-Shutoff	3.0	Aluminum	3.8
Start-up Bypass Bleed Supply-Shutoff	2.0	Aluminum	2.1
Turbine Inlet-Pressure Regulating	3.0	Steel	8.2
Turbine Nozzle Control-Shutoff	3.0	Steel	6.0
Turbine Bypass Control	1.5	Steel	2.3
Overboard Spill-Fuel Tank Pressure Control	6.0	Aluminum	6.9
Fuel Tank Supply-Low Flow Pressure Control	1.0	Steel	1.5
Fuel Sparge Flow-Shutoff Valve	1.0	Steel	1.3
Emergency Bleed Bypass-Shutoff	2.0	Aluminum	2.1
Ram Air Discharge Control-Reactor No. 1	8.0	Steel	13.1
Ram Air Discharge Control-Reactor No. 2	8.0	Steel	13.1
Ram Air Discharge Control-Reactor No. 3	10.0	Steel	16.3
Ran Air Discharge Control-Precooler	13.0	Aluminum	18.8
Reactor Discharge-Start-up Check Valve	4.0	Steel	2.3
Fuel Tank Supply-Crossover Check Valve	6.0	Aluminum	1.3
Fuel Heat Sink-Shutoff	0.75	Aluminum	1.2
Reactor Fuel Supply-Shutoff (pair)	0.25	Aluminum	1.0
Total System Valve Weight			107.3 lbs

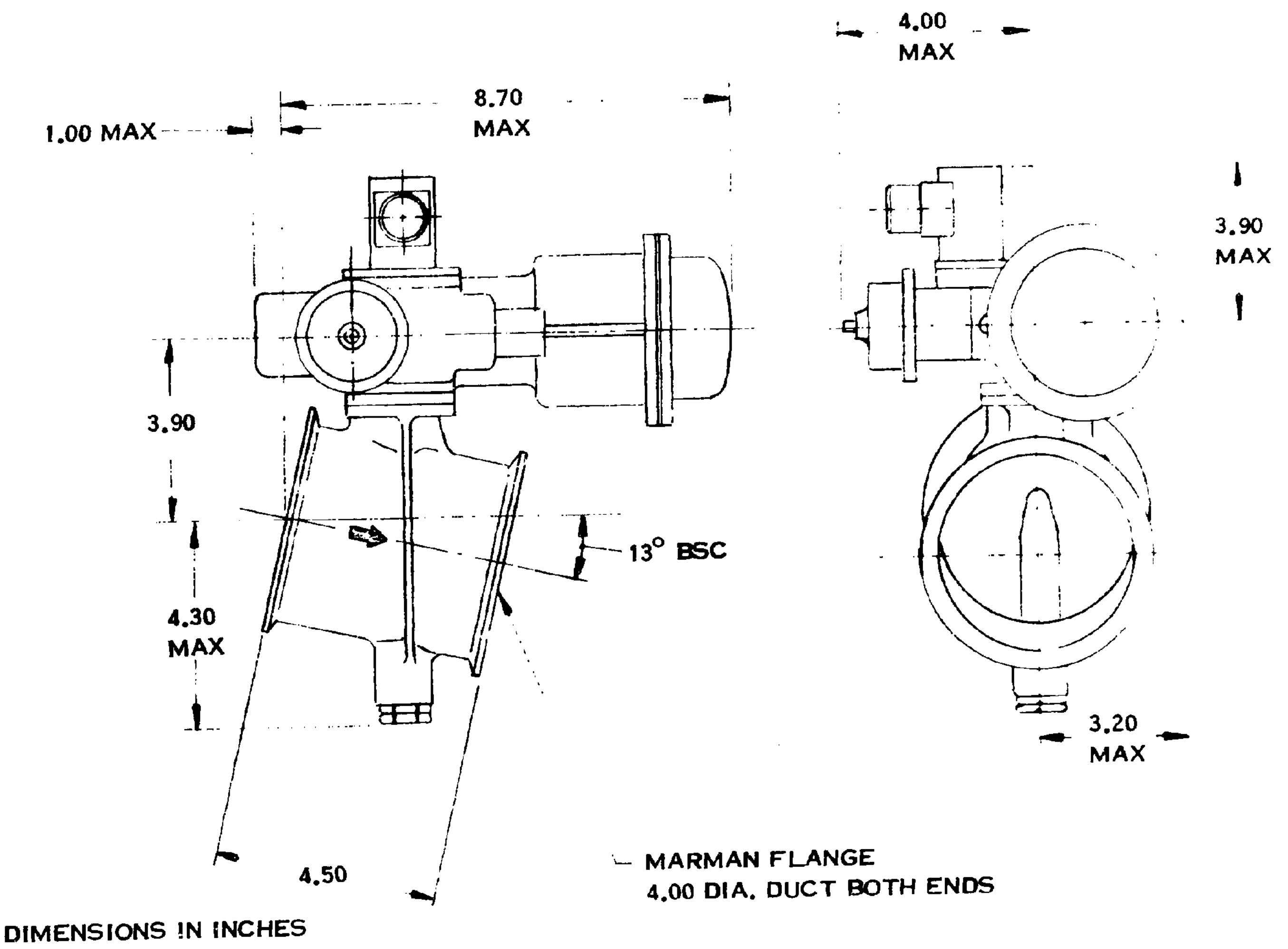


FIGURE 16. PRESSURE REGULATING AND SHUT-OFF VALVE

A typical half area actuated butterfly valve is shown in Figure 16. The dimensions are for a 4.0 inch diameter valve.

This configuration is of a proven design and is typical of existing valves used in aircraft air conditioning systems.

5.13.10 Temperature Sensors

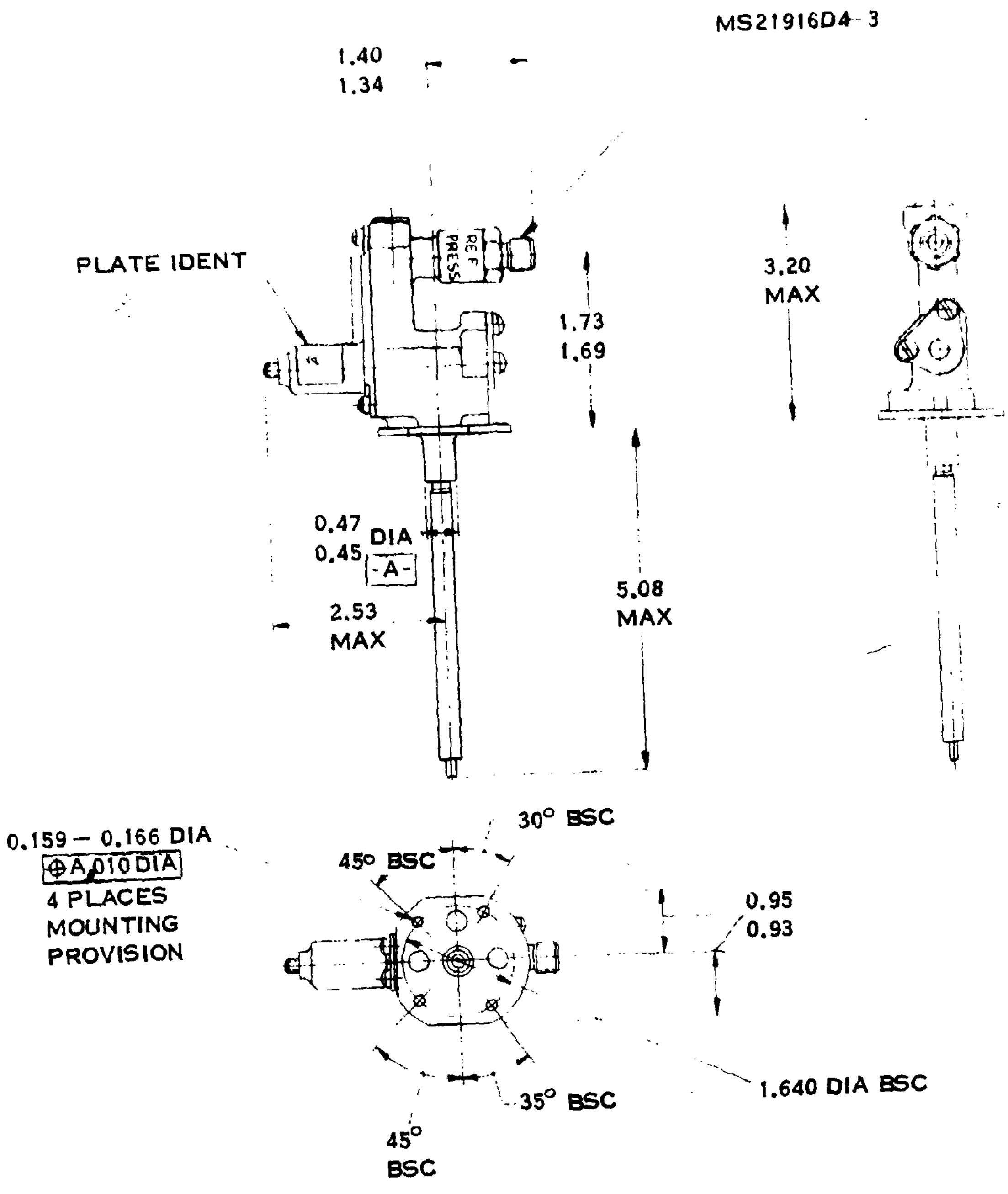
The temperature sensors utilize a coaxial rod and tube probe made of metals with different coefficients of thermal expansion. Changes in sensed temperature result in a differential expansion of the probe assembly. This differential expansion is amplified by a bell crank that compresses a biasing spring, thus changing the reference of the pressure regulator portion of the sensor. The pressure regulator portion consists of a pivoted lever, fixed orifice, variable area nozzle, and associated springs. This resulting regulated signal pressure, which is proportional to sensed temperature, acts on the controller or actuator of associated valves.

The coaxial sensing probe has an inner rod of low expansion Invar and an outer tube of high-expansion, corrosion-resistant steel. The rod and tube are joined by electron beam welding to insure repeatibility. The steel crank and lever are pivoted on close-fitting electrofilmed pins to insure accuracy.

A typical sensor is shown in Figure 17.

5.14 Installation and Weight Summary

The eventual installation configuration for this system will depend on the shape of the available space envelope. To assist in establishing the volume requirements, a tentative installation drawing has been prepared. This is shown in Figure 18 and includes a list of system components. Table V presents a weight summary for this system. Further optimization of components or design requirements could reduce this weight.



DIMENSIONS IN INCHES

FIGURE 17. RAM TEMPERATURE SENSOR

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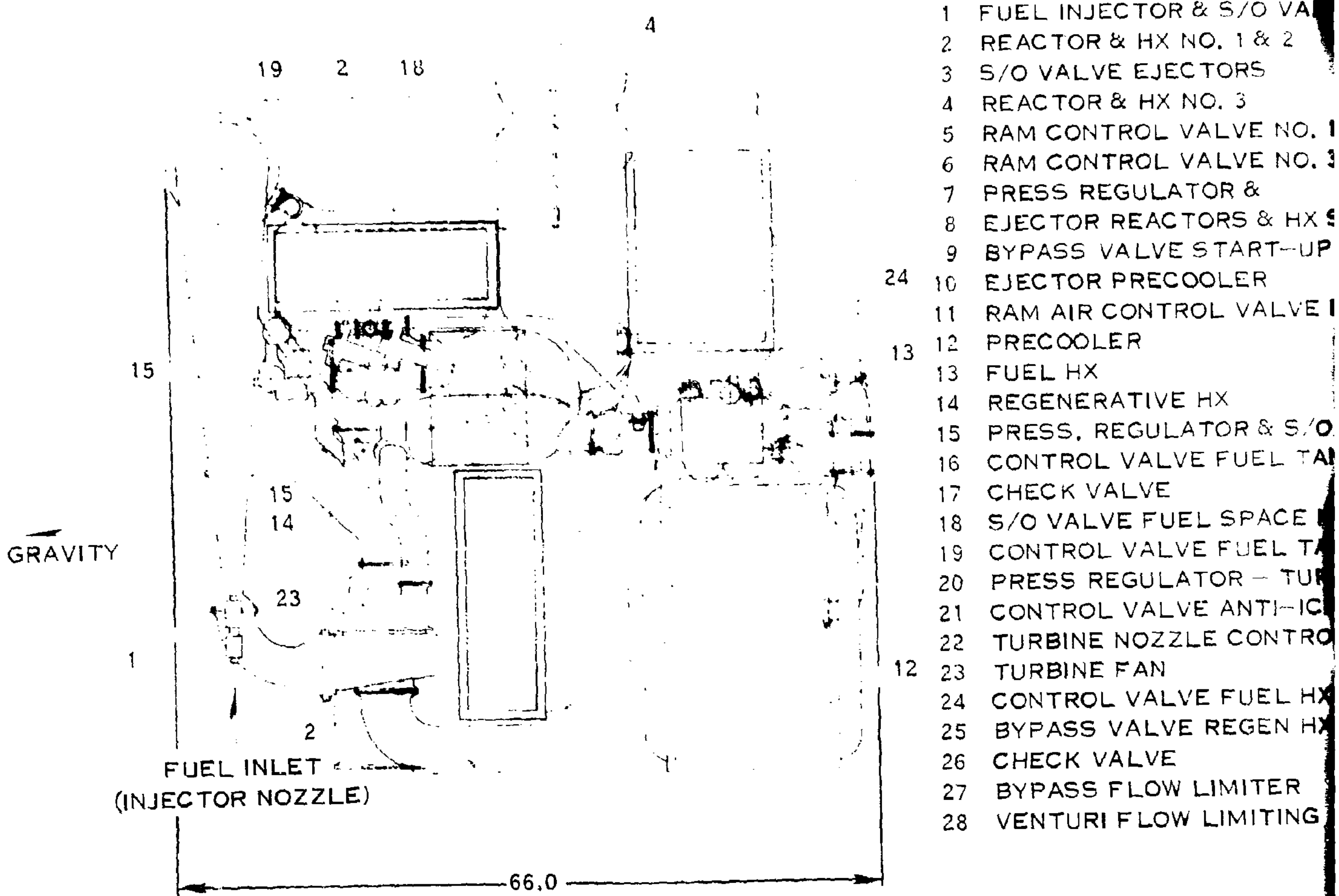

DIMENSIONS IN INCHES

OR & S. O VALVE
X NO. 1 & 2
ECTORS
X NO. 3
L VALVE NO. 1 & 2
L VALVE NO. 3
LATOR &
CTORS & HX S
/E START-UP
COOLER
TROL VALVE EJECTOR

VE HX
LATOR & S. O VALVE
LVE FUEL TANK HIGH FLOW
E
UEL SPACE NOZZLES
LVE FUEL TANK LOW FLOW
LATOR – TURBINE INLET
ALVE ANTI-ICE
ZZLE CONTROL
N
ALVE FUEL HX
LVE REGEN HX
VE
OW LIMITER
OW LIMITING

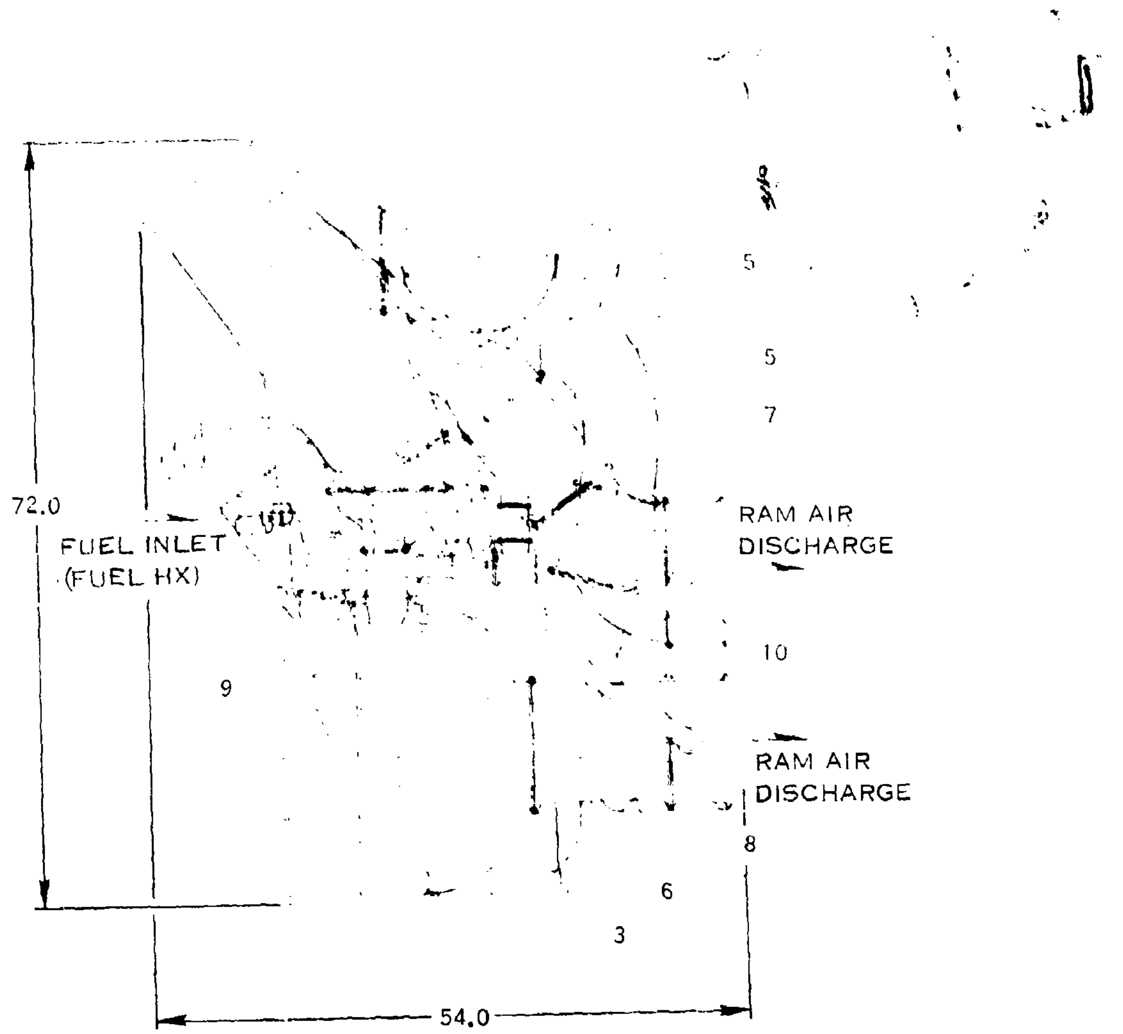

FIGURE 18. INSTALLATION FUEL TANK
INERTING SYSTEM

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Table V

FUEL TANK INERTING SYSTEM

WEIGHT BREAKDOWN

COMPONENT NAME	WEIGHT
TURBINE FAN	36
FUEL INJECTOR, NOZZLES AND SHUTOFF VALVES	9
CATALYST BED (THREE BEDS TOTAL)	142
HEAT EXCHANGERS	
REACTOR NO. 1	78
REACTOR NO. 2	78
REACTOR NO. 3	121
PRECOOLER	208
FUEL COOLED	21
REGENERATIVE	101
BYPASS REGENERATIVE	11
EJECTORS	
REACTOR RAM AIR	6
PRECOOLER RAM AIR	6
VALVES	
BLEED SUPPLY - SHUTOFF AND PRESS. REG.	6
EJECTOR BLEED - SHUTOFF	4
START-UP BYPASS - SHUTOFF	2
START-UP CHECK VALVE	2
TURBINE INLET - PRESSURE REGULATOR	5
OVERBOARD SPILL - TANK PRESSURE CONTROL	7
TANK SUPPLY - LOW FLOW PRESSURE CONTROL	2
TANK SUPPLY - CROSSOVER CHECK VALVE	1
RAM DISCHARGE - REACTOR NO. 1	13
RAM DISCHARGE - REACTOR NO. 2	13
RAM DISCHARGE - REACTOR NO. 3	16
RAM DISCHARGE - PRECOOLER	19
FUEL HEAT SINK - SHUTOFF	1
TURBINE BYPASS	2
FUEL TANK SPARGE FLOW - SHUTOFF	1
EMERGENCY BLEED BYPASS - SHUTOFF	2
TURBINE NOZZLE CONTROL	3
TOTAL COMPONENT WEIGHT	916

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6.0 SYSTEM PERFORMANCE

6.1 System Design Point Performance

Design requirements for the system specify a maximum oxygen content in the tanks which will assure a noncombustible mixture at all flight conditions and a maximum moisture content in the inert gas being supplied to the tanks. Early surveys of the various flight conditions indicated that the most stringent requirements existed during descent. More specifically, the worst conditions and the condition which has been used as a design point for this system is 3,000 ft descent at minimum flight speed and minimum engine power. This condition on a hot day combines in several areas the worst conditions which can be encountered with this system. Considering the two basic requirements separately, it should be noted that the oxygen concentration in the inert gas is substantially below combustible limits. It was necessary to design for this degree of inerting at this flight condition so that at emergency descent conditions, an inert mixture would always exist in the fuel tanks. An alternate approach would have been to use a secondary system to meet these emergency descent requirements. This secondary system would add significant complexity to the overall system and not have the side benefit of the selected system of having a significant margin of inertness at normal flight conditions. This margin in oxygen content can accommodate such things as deterioration of catalyst operation with time and changes in oxygen content during transients or purging operations.

This condition by itself represents the most severe case in terms of meeting basic moisture requirements. The combination of low bleed pressure, low ram pressure drop, and high ram temperature all tend to make the moisture removal process more difficult. These conditions, as compared to those under all other flight conditions, have resulted in a significantly greater heat exchanger size. Any change to this 3,000 ft condition in terms of higher pressures or decreased requirements would have a significant effect on overall system sizes and weight. An example of this will be shown in the off-design performance where, for example, at 25,000 ft descent, significant throttling of the ram air is possible while maintaining required moisture content.

The performance at the design point condition is illustrated in Figure 19. The bleed conditions were obtained by extrapolation of the bleed data and include a loss of 10% between the engine and the system. The combustor characteristics, although not identical to the test data, were substantiated by the test data. Heat exchangers were sized at this condition, including

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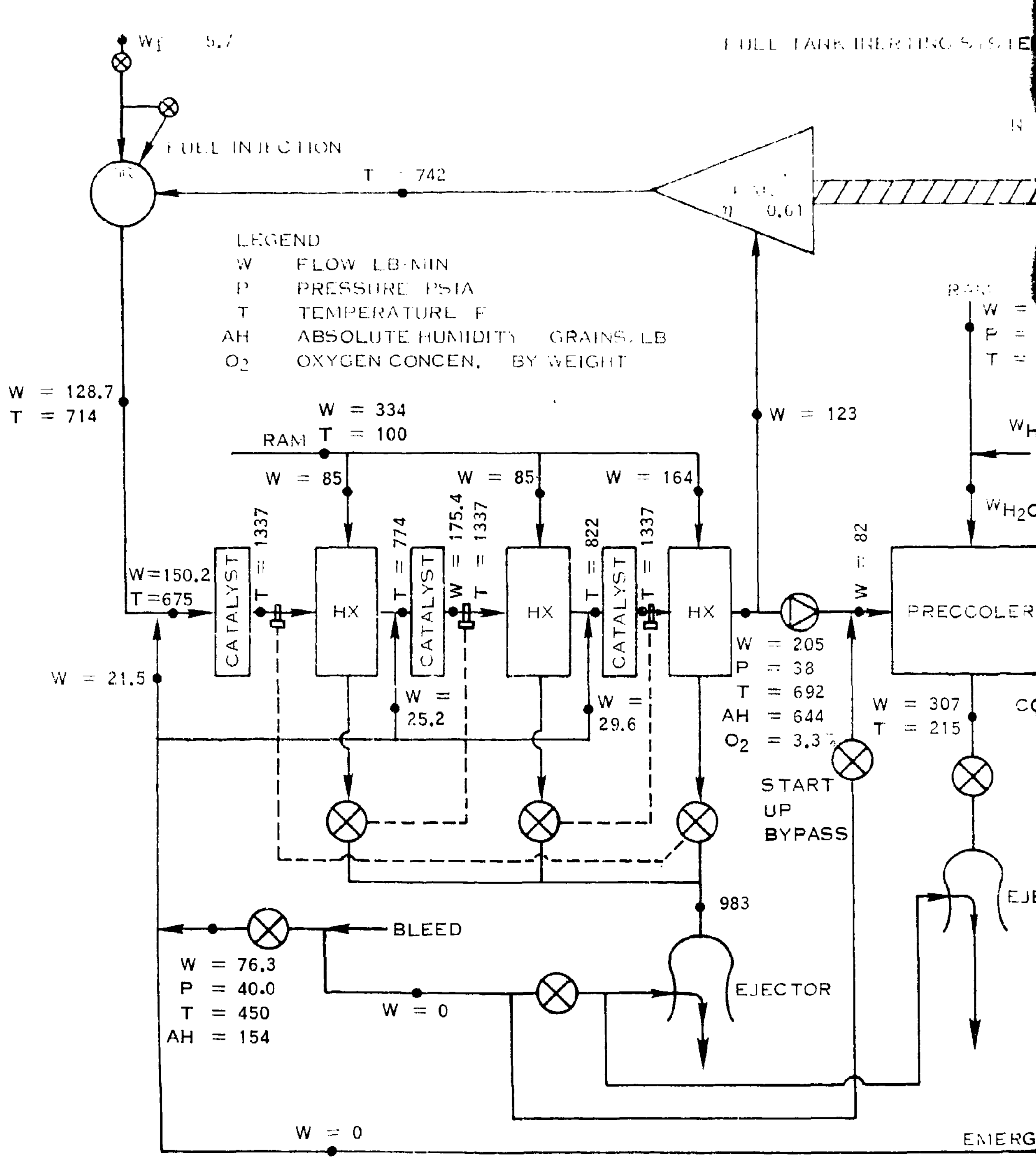

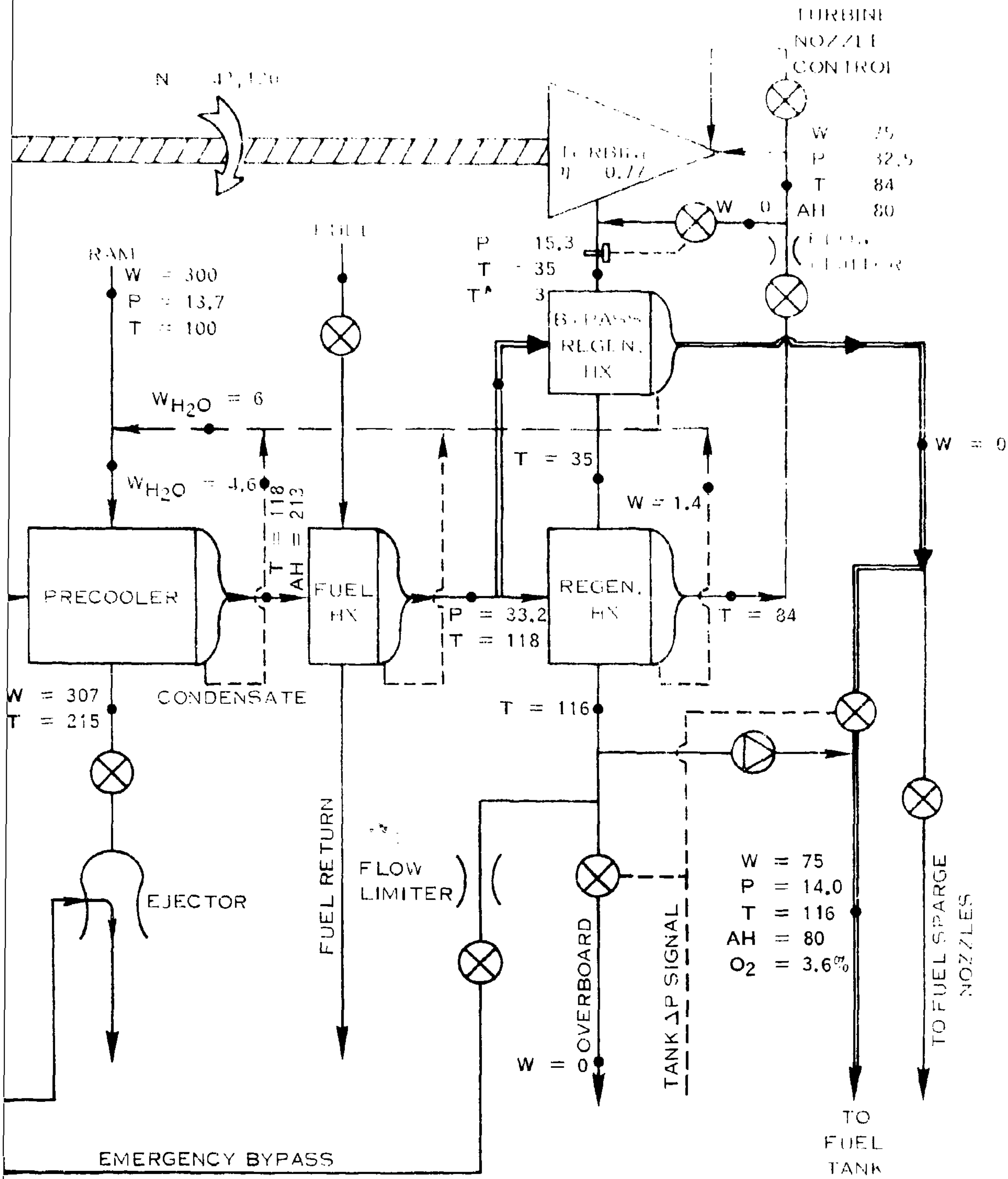

FIGURE 19. 3,000 FT. IDLE DESCENT – DESIGN POINT

2

the effects of condensation and/or evaporation wherever it occurs. The turbomachine performance characteristics were evolved from test data on similar machines. The performance of the system includes anticipated pressure losses between components although installation could alter these losses slightly. It can be seen from this flow chart that design requirements for moisture are met and for oxygen content are exceeded by a substantial amount.

The performance at this design point condition as well as several off-design point conditions has been analyzed through the use of a computer program to assure that the performance at all conditions would be adequate. This analysis has properly accounted for the effects of the changing fluid composition, the most important of which is the condensation occurring in the heat exchangers of the moisture removal subsystem. The latent load on these heat exchangers that is a result of this condensation is very significant, particularly in terms of heat exchanger size. The amount of moisture condensed is several times the amount that occur in aircraft ECS.

6.2 System Off-Design Performance

Performance of the inerting system was analyzed for a number of normal off-design operating conditions selected for their critical nature in terms of the moisture content of the gas supplied to the fuel tanks. Also, an analysis of an emergency descent was conducted to demonstrate that the worst case fuel tank oxygen concentration remains within the safe range.

6.2.1 Low Altitude Dash

The system performance during a low altitude dash is shown in Figure 20. The system is operating in the low-flow mode with all ram flows greatly throttled, with the turbine nozzle at partial admission and with essentially complete conversion of oxygen predicted for the catalytic reactor. The temperature rise across the catalyst beds is down from the 500-600°F level to approximately 200°F due to the greatly increased ratio of recycled inert gas to fresh air added. This, in turn, is due to the fact that although the turbine flow was reduced by almost 90% of the design point flow, the recirculating fan flow dropped by only 44%. This circumstance allowed the reduction of the maximum temperature in the reactor while keeping the average catalyst temperature at approximately 1000°F.

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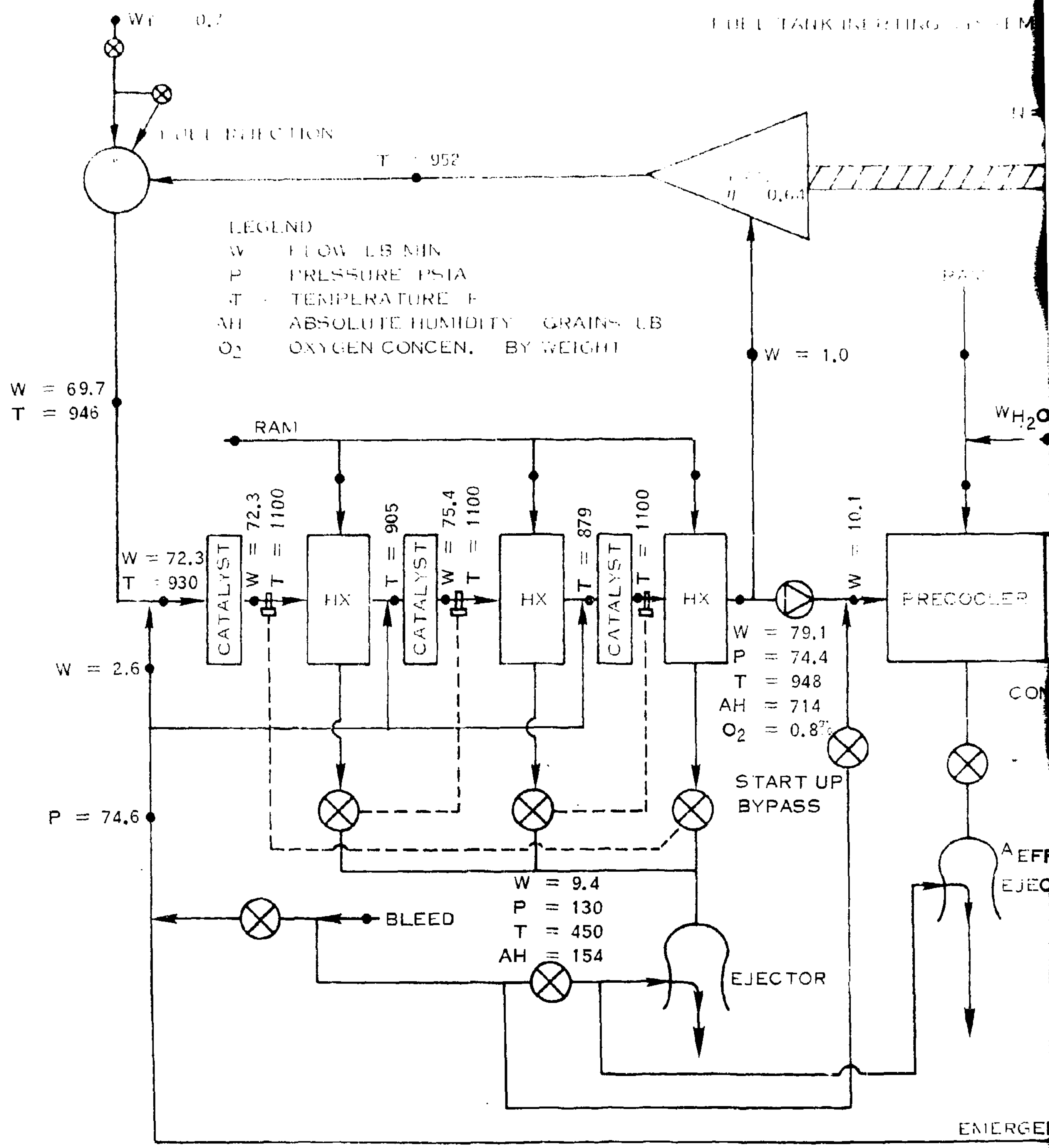

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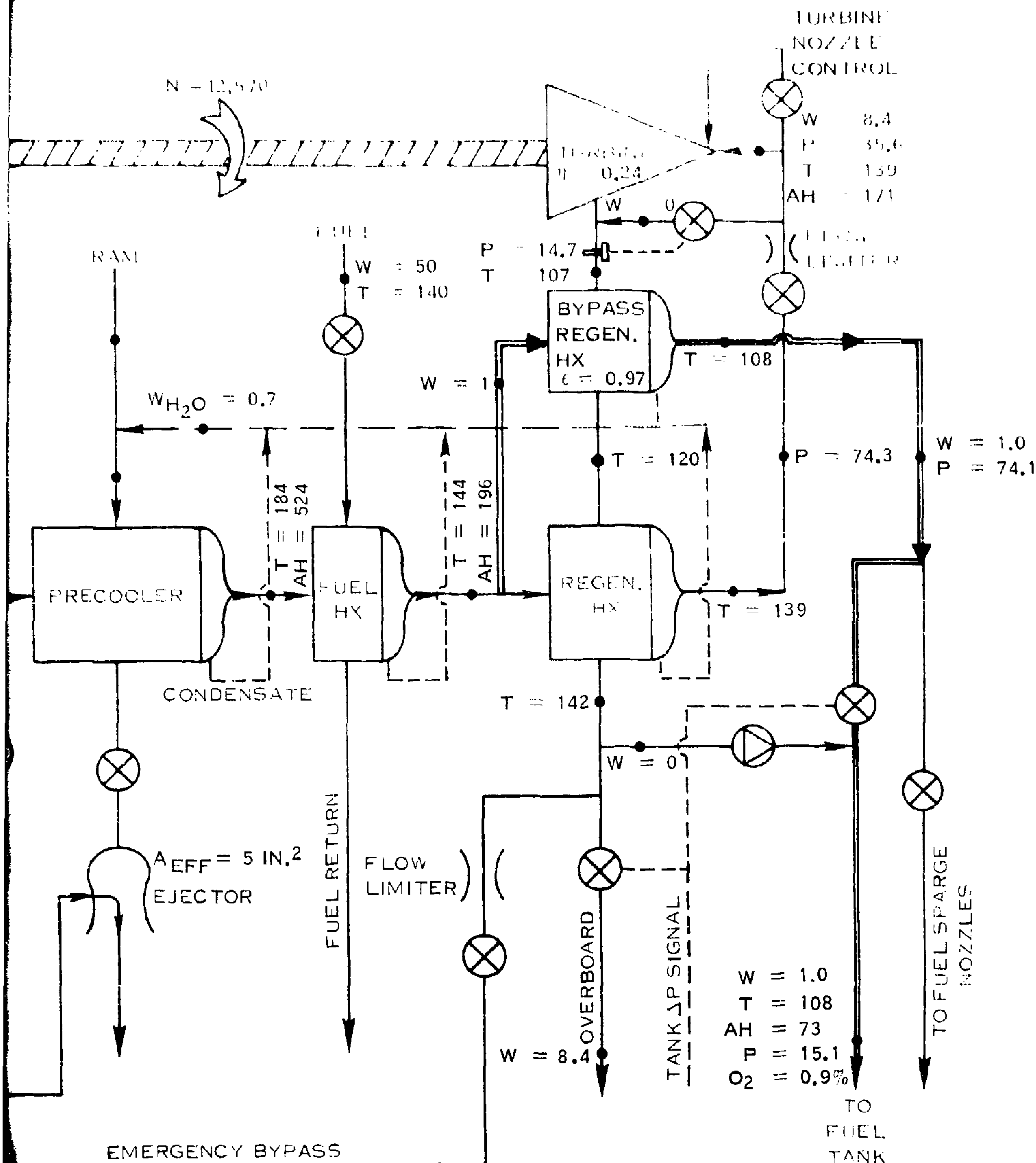

FIGURE 20. LOW ALTITUDE DASH (IN)

The low altitude dash condition represents the operating point with the highest heat sink temperature over the specified subsonic mission profile. The fuel-cooled heat exchanger was sized for this condition so that the moisture content in the gas supplied to the fuel tanks is below the 80 grains per pound that was specified as the maximum allowable. This was accomplished by combining a 90% effective fuel heat exchanger with the highly effective bypass regenerator which provided cooling to 108% at approximately 74 psia. A flow of 1.0 lb per minute is supplied to the tanks while the turbine flow of 8.4 lb per minute flows overboard. System pressure is throttled both at the bleed supply point (60 psig) and the turbine inlet (21 psig).

6.2.2 High Altitude Dash

The system performance during a high altitude dash condition is shown in Figure 21. The system is operating in the low-flow mode. This operating point has the highest heat sink temperature over the specified supersonic mission profile. The bypass regenerator was sized for this condition so that the moisture content in the inerting gas supply is less than the 80 grains per pound maximum limit. At this condition, considerably more turbine cooling is made possible by expanding to the low ambient pressure. The flow chart shows the bypass regenerator at 80% effectiveness providing cooling to 81°F at 31.5 psia, bringing the absolute humidity to 73 grains per pound.

6.2.3 25,000 Foot Idle Descent

The system performance during descent at 25,000 ft with idle engine power is shown in Figure 22. This condition demonstrates the operation of the anti-ice turbine bypass control. The system is operating in the high-flow mode with 60 pound per minute of dry gas being generated, although only 38 lb/min satisfies the demand for fuel tank pressurization. The precooler ram flow is throttled to hold 90°F on the hot-side discharge. It is desirable to keep this temperature high so as to minimize the anti-ice bypass flow, however, a low temperature is dictated by moisture removal requirements. The performance chart shows that 90°F provides for a moisture content of 80 grains per pound under this low pressure condition.

In the combustor section of the system it is noted that the recirculation flow ratio is below the design point value due, mainly, to the power-reducing effect of the turbine bypass. Since the effect of reduced recirculation is increased temperature rise in the catalyst, and the bed discharge temperatures are held to the maximum control setting of 1337°F (725°C), the result is reduced catalyst inlet temperature. This, in turn, causes a shift downward in the oxygen conversion rate and, hence, a

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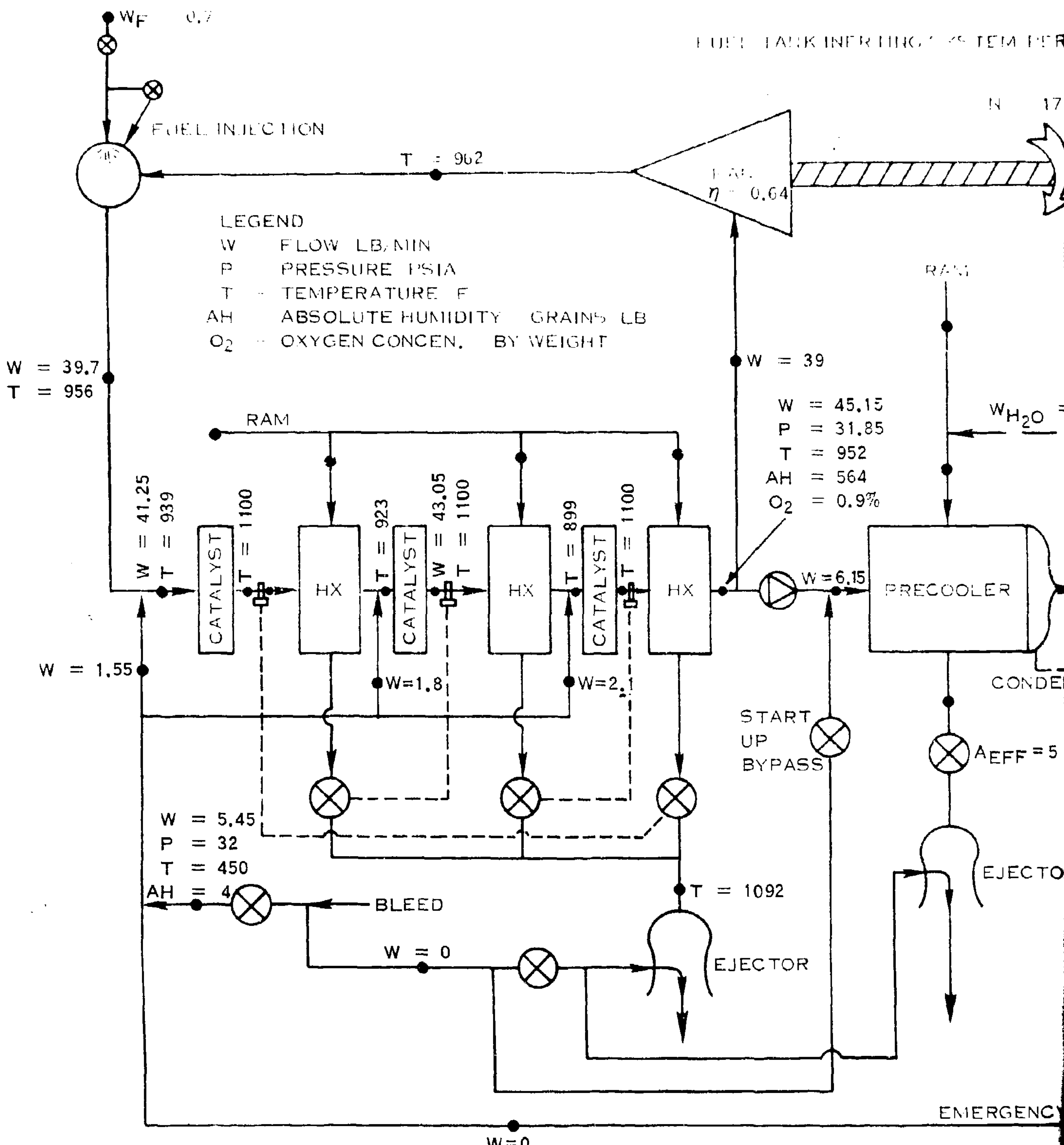

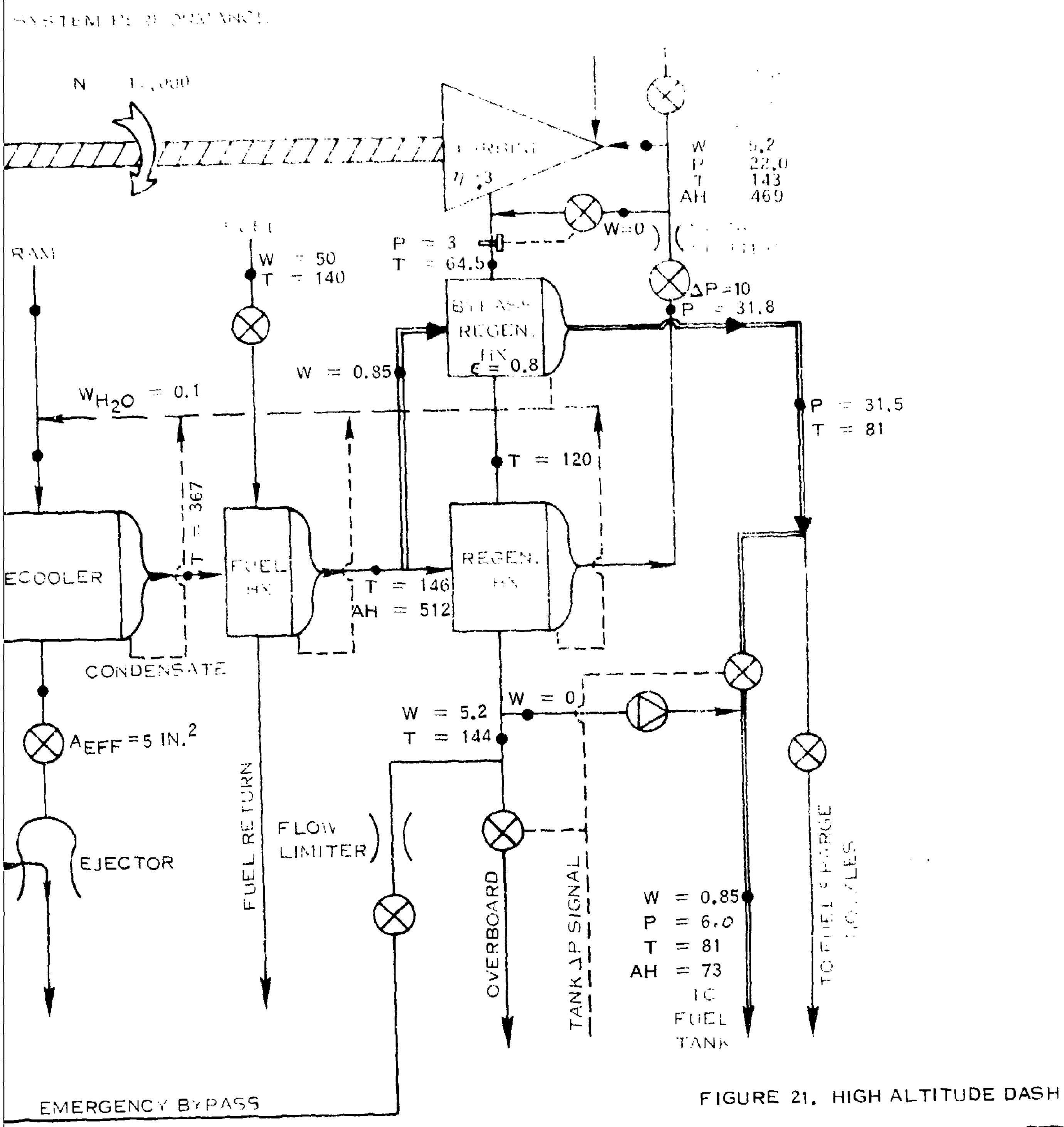

FIGURE 21. HIGH ALTITUDE DASH

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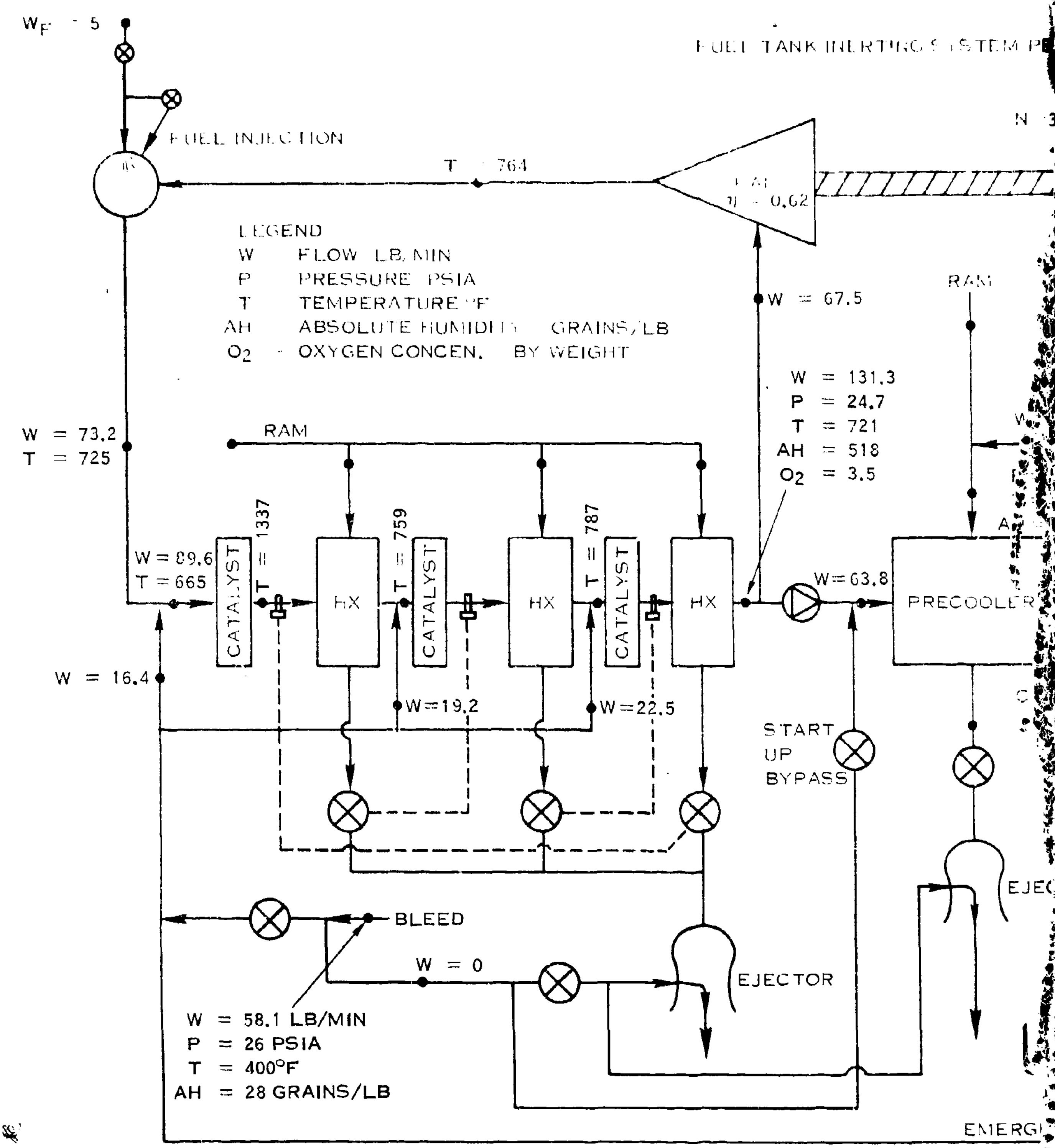

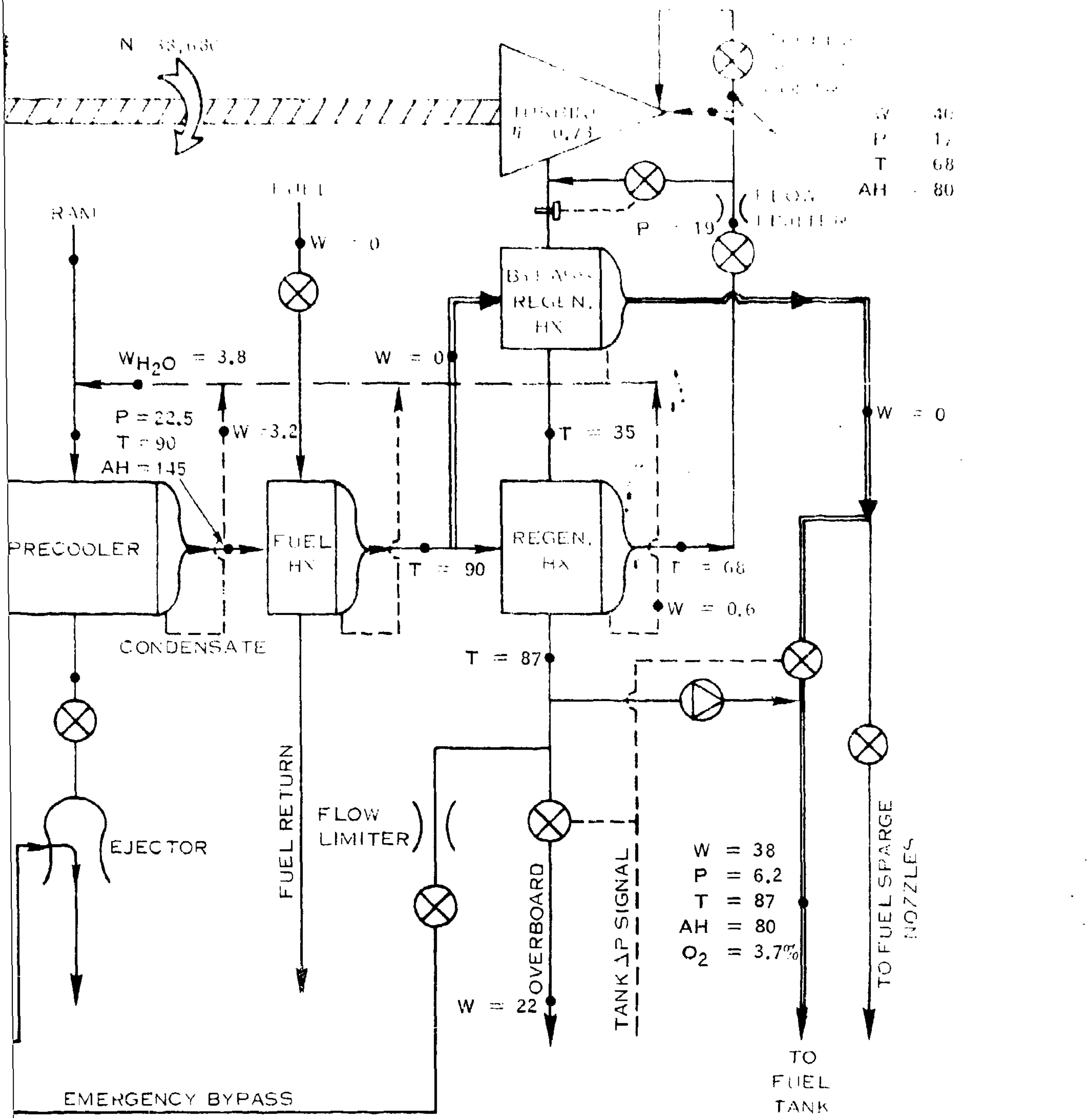

FIGURE 22. 25,000 FT IDLE DESCENT

tendency toward reducing the temperature rises. The performance chart indicates an estimate of the resulting steady-state operating condition.

6.2.4 Cruise Performance

System operation during cruise is on the low-flow mode. The flow demand to maintain fuel tank pressure is extremely low, typically on the order of 0.1 lb/min. The 90°F precooler discharge and 35° turbine discharge controls will be on and the temperature of the flow to the tanks will be about 40°F. At typical bleed pressures of 30 to 50 psia, the moisture content during cruise operation will be less than 20 grains/lb.

6.2.5 Emergency Descent Performance

In the event of an emergency descent, when the rate of change of fuel tank pressure could be as much as 2.5 times the maximum normal rate, the emergency bypass line is opened to supplement the inerting system flow in order to maintain fuel tank pressurization. An analysis performed showed that the oxygen concentration in the fuel tanks does not exceed 9% under worst-case conditions. The assumptions made in this analysis are as follows:

a. The ullage space is initially inerted with the oxygen concentration possibly as high as 3%.

b. The fuel tanks are near empty.

c. The tank pressure at the start of the dive is 6 psia at 25,000 ft and is maintained at 0.5 psig to 3,000 ft.

d. The bleed air bypass flow is used as make-up flow to the extent that the system flow is deficient in meeting the demand for pressurization.

e. The oxygen concentration in the inerted gas is 4%.

Figure 23 summarizes the emergency descent performance. It can be seen that the oxygen concentration just reaches 9% at an aircraft altitude of 3,000 ft. Since it is not likely that the emergency dive rate would be maintained to such a low altitude, it may be assumed that this method of satisfying emergency fuel tank pressurization would result in a final oxygen concentration of less than 9%.

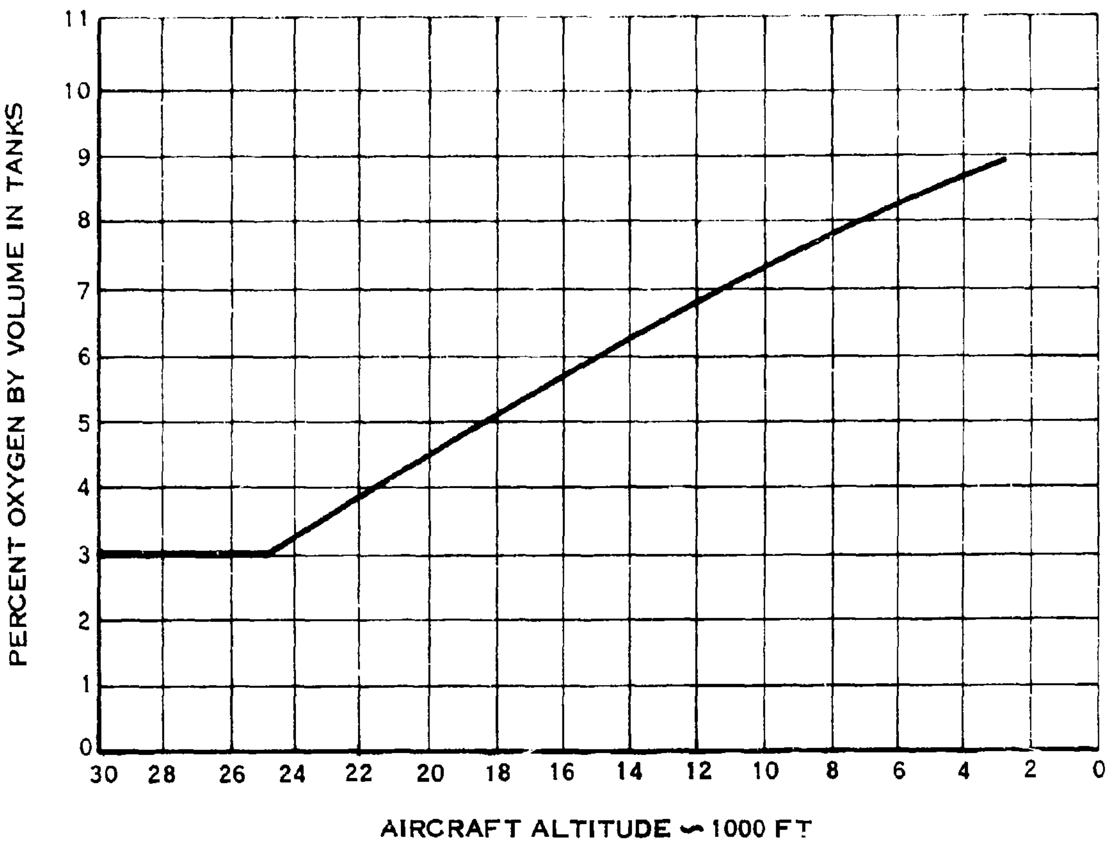

FIGURE 23. B-1 FUEL TANK INERTING SYSTEM PREDICTED FUEL TANK OXYGEN EMERGENCY DESCENT TANKS NEAR EMPTY

6.3 Inerting System Overall Mission Performance

An evaluation of the inerting system performance with an overall mission viewpoint may be made through the use of basic penalty factors. The system defined through the preliminary design study was sized for a B-1 Long Range Bomber with a stated fuel tank capacity of approximately 40,000 gallons, or almost 250,000 pounds of JP-4 fuel. The fuel tank capacity is the main factor in describing the aircraft penalties incurred by operating the system. For example, the estimated take-off weight added by the system is approximately 0.5% of the aircraft fuel capacity.

The overall mission performance, when measured in terms of added fuel consumption, must be considered in two parts: direct and indirect. In terms of direct fuel consumption, that is, fuel actually consumed in the catalytic reactor, the inerting system requires approximately 0.02% of the total aircraft fuel capacity per mission hour. Indirect fuel consumption is attributable to bleed air usage and ram drag penalties. A first order approximation of these effects over the specified mission profiles suggests that an additional fuel penalty of 0.01% of the fuel capacity per mission hour is consumed by the inerting system. For a 10 hour mission, for example, the total penalty amounts to 750 pounds of JP-4. Of this total, about 650 pounds is consumed during the long duration cruise when the actual demand upon the system is minimum. However, due to the continuous operation of the system, a steady overboard flow of inert gas causes considerable penalty to be incurred. Analysis shows that the use of intermittent system cperation could bring about a major reduction in this penalty. Such operation could be based upon a demand control, wherein cyclic fuel tank pressurization, within the pressure control tolerance band, was obtained. However, this scheme would rely on frequent start/stop cycles which is undersirable from the viewpoint of catalyst bed performance. Also elimination of the overboard flow line would tend to substantially increase the moisture content of the gas flow to the tanks due to the removal of the highly effective bypass regenerator.

Analysis of the moisture content in the inert gas delivered to the fuel tanks over the specified long range missions indicates that approximately 1.5 gallons of water are added over one subsonic and one supersonic mission. This corresponds to 0.00375% of the total fuel tank volume and is comparable to the water added by a hot day atmosphere when the fuel tanks are pressurized with engine bleed air.

The significance of this apparently small amount of water contamination in the B-1 fuel system is difficult to estimate. Experience in humid climates has provided evidence of difficulties due to the accumulation of water in the fuel systems. The fact that the moisture added by the inerting system will be slightly acid due to dissolved products of combustion adds to its undersireability in even the slightest amounts.

7.0 CATALYTIC REACTOR EXPERIMENTAL PROGRAM CONDUCTED BY AMERICAN CYANAMID COMPANY

7.1 Background

In the prior program * relating to catalytic combustion for fuel tank inerting, only a limited amount of work was done with liquid fuels. The general feasibility of the approach was demonstrated but there was little exploration of the many variables involved. Most of the work was carries out with JP-7, a highly paraffinic fuel with higher and narrower boiling range than the JP-4 fuel of present interest, and containing very little sulfur. The space velocity range studied was 32,000 to 150,000 hr^{-1}. Stoichiometric mixtures, 2 inch thick catalyst beds, and inlet oxygen concentrations of 3.5-4% were used in most runs.

The data obtained from this program, while limited, provided a preliminary estimate of the reaction rate constant for use in the design analysis covered in paragraph 5.2 of this report. There was also some indication that the reaction was increased by operating with an excess of fuel or at pressures somewhat above atmospheric. Reasonable catalyst stability was demonstrated in one run of 60 hours duration, using an excess of JP-4 fuel, and operating at a space velocity of 100,000 hr^{-1} with a conversion level of about 95% or greater.

With this prior work as a starting point, the general objectives of the present program were defined as follows:

a. Investigate the relationships among space velocity, temperature, and conversion under conditions simulating actual operation. Determine how these relationships are affected by variations in gas composition and system pressure.

b. On the basis of the above data, determine the minimum temperature required to initiate ("light-off") the reaction, and re-evaluate the reaction rate constant used in the design analysis.

c. Investigate the problems associated with starting up the reactor, using undiluted air.

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* AFAPL-TR-69-68

d. Obtain pressure drop data to confirm the relationships utilized in the design analysis.

e. Investigate the composition of the reactor exhaust gas, particularly with respect to carbon monoxide, sulfur and nitrogen oxides.

f. Determine minimum practical bed thickness as determined by either "light-off", or by conversion at design flows.

g. Obtain some information with respect to transient behavior of the reactor system.

Within the limited time available for experimentation, it was not possible to actively pursue all of the objectives outlined above. Major emphasis was placed on objectives (a), (b), (d) and (e). The question of minimum practical bed thickness was not pursued experimentally because the design analysis indicated that for the B-1 bomber application, the use of beds thinner than one inch would result in excessive cross-sectional area requirement.

The experimental approach to obtaining the information outlined above was guided by the results of the design analysis presented in paragraph 5.2. Thus, most of the runs were made at either 300,000 hr^{-1} or 30,000 hr^{-1} space velocity (representing the high- and low-flow modes of operation). The choice of inlet oxygen concentrations used in these runs (approximately 6% at high flow and 3% at low) was also governed by the design calculations.

7.2 Experimental System

7.2.1 Apparatus

The experimental system (Figure 24) is composed of four subsystems:

- Fuel feed and vaporization
- Gas and water feed (including water vaporization)
- Reaction
- Sampling and analysis

The system is designed to operate at pressures up to 100 psig, and to handle throughputs of up to about 1 lb/min.

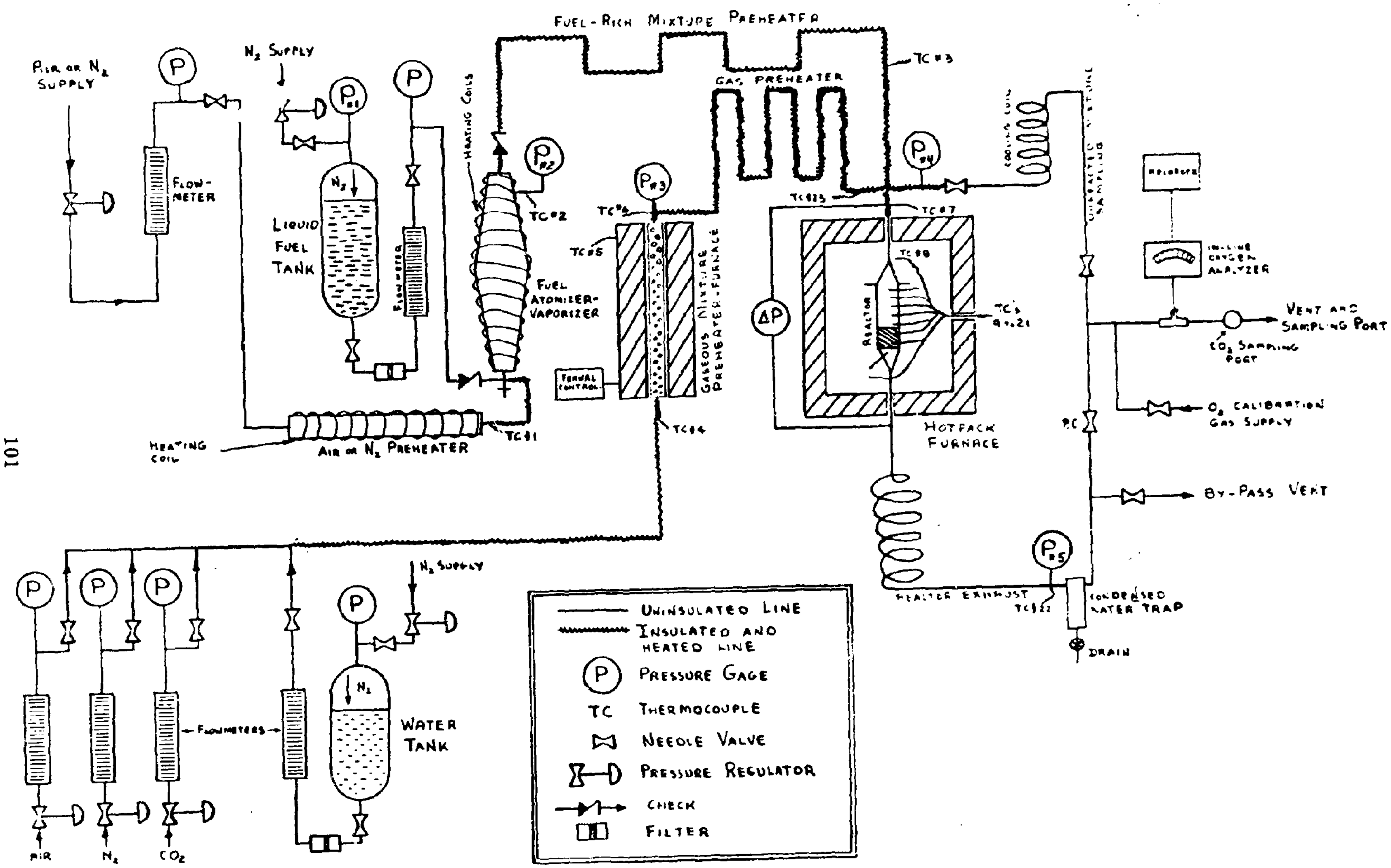

FIGURE 24 SCHEMATIC DIAGRAM OF CATALYTIC COMBUSTION TEST UNIT

a. Fuel Feed and Vaporization Subsystem

This subsystem consists of a liquid fuel tank, a liquid fuel rotameter, and a heated vaporization chamber. The tank is pressurized with nitrogen to force the fuel through a two-fluid atomizing nozzle into the vaporization chamber. The atomizing fluid is normally preheated nitrogen. The vaporized mixture is further preheated in the line leading to the reactor. All heating is done by means of Nichrome resistance wire coiled around the chamber and connecting tubine. Thermocouples and pressure gages are strategically located.

b. Gas and Water Feed Subsystem

Air, carbon dioxide, nitrogen and water are fed through individual rotameters into a heated blending and vaporization line. Water is fed as a liquid from a pressurized feed tank and is introduced axially into the horizontal vaporization line through a small-diameter injection tube. The gas mixture is further preheated in a packed-column furnace and in the line between that furnace and the reactor. Again, pressure gages and thermocouples are conveniently located.

c. Reaction Subsystem

The two streams of preheated gases and vapors combine and discharge into the reactor, which is located inside an electric furnace (Hotpack, Model 7075). The reactor exhaust gases pass through a helical cooling coil (air or water cooled) where water is condensed and removed by means of a trap. Uncondensed vapors and gases leave through the PC valve, which is a needle valve used to control system pressure.

The reactor and the furnace are instrumented with pressure gages, thermocouples and a differential pressure gage. Most of the thermocouples inside the reactor are inserted radially, as shown schematically in Figure 25. Thermocouple (TC) Nos. 9, 10, 11, 12, 13 and 19 are straight and have their sensor-tips centered inside the reactor to give axial temperatures. TC's 17 and 18 are bent so that their tips are about 1/8 inch distant from the reactor wall. TC 21 is located in the reactor wall, while TC 20 is centered immediately below the bed supporting screen. (TC's 14, 15 and 16 shown in the figure were not installed).

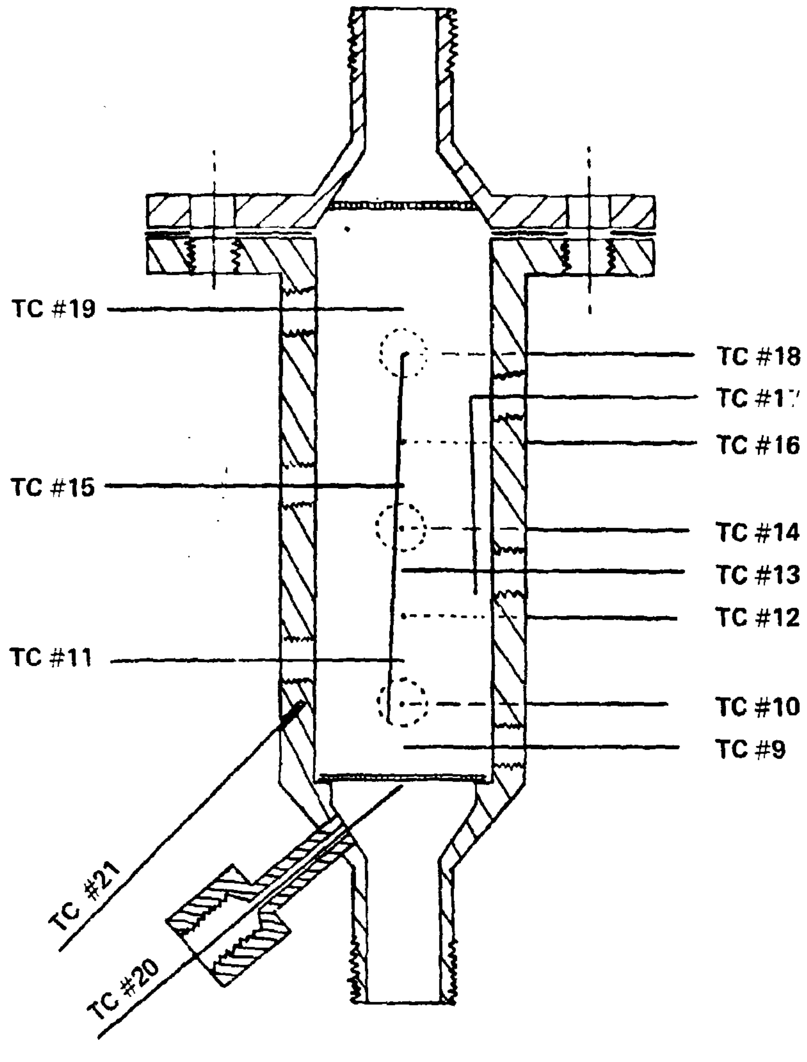

FIGURE 25. ONE INCH I.D. REACTOR
(INCLUDING LOCATION OF THERMOCOUPLES)

All thermocouples are connected to a 24-point temperature recorder (Minneapolis-Honeywell, Model Y153X89-(C)-II-III-16) which operates on a two-minute cycle and covers a temperature span of 0-1000°C.

d. Sampling and Analysis Subsystem

This subsystem consists of a continuous in-line oxygen analyzer, and various sampling arrangements used to obtain off-gas and condensate samples for intermittent analyses. The analytical methods and equipment used are described in more detail in paragraph 7.2.4.

7.2.2 Materials

a. Equipment

All components of the experimental system in contact with the reactants are made of type 316 stainless steel.

b. Catalyst

The catalyst employed in this experimentation is American Cyanamid Company's AERO-BAN R Catalyst. It is an oxidation catalyst furnished as 1/16 inch diameter extrudates having an average length of 1/8 inch, and a bulk density of 40.6 lb/ft^3.

c. Fuel

The fuel used is referee grade JP-4, conforming to Mil-T-5161G specification. A complete analysis of the lot employed (Batch No. 3-70-COV) was submitted by the supplier (Ashland Oil, Inc.) and is reproduced in Table VI.

For computational purposes, the fuel is assumed to have an equivalent composition of $C_{10}H_{20}$, with a corresponding molecular weight of 140.

d. Other Materials

Air	-	ambient air from a reciprocating compressor
N_2	-	99.998% pure, from liquid nitrogen cyclinders (Linde Division, Union Carbide Corporation)
CO_2	-	99.997% pure, from gas cylinders (Air Reduction Co.)
Water	-	distilled

Table VI - Fuel Analysis

COVINGTON 311 TANK - REFEREE GRADE I MIL-T-5161G

	Mil-T-5161G Specification	Batch 3-70-COV Covington, Ky. (4/10/70) Top	Mid.	Btm
Gravity, °API	50-57	55.0	55.1	55.1
Distillation, °F - IBP	Report		150	
10% Evaporated	200 max		187	
20% Evaporated	180-230		204	
50% Evaporated	230-275		258	
90% Evaporated	325-370		358	
EP	450 max		446	
Recovery, %	Report		98	
Residue, %	1.5 max		1.0	
Loss, %	1.5 max		1.0	
Existent Gum, mg/100 ml	7 max		2.9	
Potential Gum, mg/100 ml	14 max		5.4	
Total Sulfur, weight %	0.15-0.40		0.165	
Mercaptain Sulfur, weight %	0.005 max		0.0005	
Reid Vapor Pressure, 100°F, psi	2.0-3.0		2.65	
Freeze Point, °F	-67 max		-80	
Aniline Point, °F	Report		104	
Net Heat of Combustion, BTU/lb	18,400-18,750		18,690	
Aniline Gravity Product	5,250-7,000		5,730	
Aromatics, Volume %	10-25		24.9	
Olefins, Volume %	5 max		0.7	
Smoke Point, mm	Report		17	
Copper Strip Corrosion	1 max		1a	
Water Reaction	1b max		1	
Viscosity, cs at -30°F	Report		1.74	
Water Separometer Index Modified	85 min		98	

(Table Continued)

Table VI (continued)

	Mil-T-5161G Specification	Batch 5-70-COV Covington, Ky. (4/10/70)		
		Top	Mid.	[illegible]
Thermal Stability (300/400/6)				
Filter Pressure Drop, In. Hg	15 max		0.0	
Preheater Rating	3 max		1	
Anti-icing Additive, Volume %				
Top	Report		0.145	
Middle	Report		0.144	
Bottom	Report		0.145	
Composite	0.12-0.15		0.145	
Metal Deactivator: N,N'Disalicylidene-1-2-Propanediamine, lbs/1000 bbls	1.5-2.0		2	
Antioxidant: 2,6 Ditertiary Butyl-4-Methyl Phenol, lbs/1000 bbls	5.0-8.4		8	

7.2.3 Operating Procedures

a. General

(1) Flow of Gases. The flows of the gases are regulated individually by means of pressure regulators, calibrated indicating rotameters and precision needle valves.

(2) Flow of Liquids. The rotameters for the fuel and water are calibrated for use with these fluids in the liquid phase at a temperature of 72.5°F. For computational purposes, it is assumed that the superheated vapors behave as ideal gases.

(3) Analytical Instruments. The oxygen analyzer and Carle gas chromatograph are calibrated with gas mixtures of known composition (chromatographically determined). Provision is made to permit checking the calibration of the oxygen analyzer while a run is in progress.

(4) Use of the Furnace. During low space velocity runs, the feed subsystems do not preheat the entering streams sufficiently and additional heat must be added by means of the furnace surrounding the reactor, which can be set at any desired temperature of interest in this program. For high space velocity runs, the reactor furnace is not used for supply of additional heat but as an insulated chamber. In the latter situation, the cavity between the reactor and the furnace is filled with glass wool.

b. Charging the Reactor

For a given run, a fresh charge of catalyst may be required, depending on the purpose of the run and on the condition of the catalyst in the reactor after prior usage. The required volume of catalyst is weighed, placed in the reactor on top of the support screen and leveled out. The thickness and uniformity of the bed are checked and the reactor head is bolted on. The reactor is then placed inside the furnace and all thermocouple connections made.

In some cases, a 1/4 inch thick bed of inert granular material was placed on the support screen before charging the catalyst. This made it possible to obtain a better definition of the temperature profile in the vicinity of the exit plane of the catalyst bed. The inert material used is identical to the catalyst in size and shape.

c. Start-Up

Once the inlet and outlet connections to the reactor have been made tight and leak tested, the following stepwise start-up procedure is initiated:

(1) A small flow of nitrogen (about 4 ℓ /min) is directed through the various sections of the test system.

(2) All of the Variacs (voltage regulators) in the feed subsystem are set to the required voltage, and power is switched on. Heat-up of the entire system to the desired temperature takes about two hours.

(3) The oxygen analyzer is calibrated using a standard gas (4% oxygen in nitrogen), and a check is made on the nitrogen flowing through the system.

(4) Upon completion of heat-up, the full flow of each of the component gases (for the particular space velocity and composition desired) is turned on in the following order: nitrogen, carbon dioxide, and air. The feed mixture is checked for its oxygen content and adjusted if necessary.

(5) If the run is to be made under pressure, pressure is built up in the system by means of the PC valve and necessary adjustments made to pressure regulators and rotameters.

(6) Over a brief period of time, temperatures in the system adjust to new levels. Adjustments are made to the Variacs as necessary to obtain the desired temperature of the mixture entering the catalyst bed. In the case of low space velocity runs, final control is achieved by means of the reactor furnace.

(7) Once the desired feed temperature, pressure, and composition have been established, the flow of fuel is begun. This marks the start of the run.

d. Run Procedure

In general, during a run, space velocity, feed composition (other than fuel vapor), and pressure are maintained constant while the effects of changes in fuel-to-oxygen ratio and inlet (feed) temperature are

investigated. Fuel-to-oxygen ratio is evaluated by first establishing a base-line operation at the stoichiometric ratio, then increasing the fuel flow stepwise. At appropriate intervals, temperatures and other conditions are logged, analyses made, and samples taken. This procedure is repeated to evaluate the effect of increasing inlet temperature levels, while exercising caution not to run with fuel-to-oxygen ratios that are likely to overheat the catalyst bed. (In the event that an excessive catalyst temperature is observed, fuel flow is shut off.)

In special runs, operation at elevated pressure and in the presence of water vapor were studied. In the latter case, the inlet concentration of oxygen was held constant by reducing the flow of nitrogen diluent as the water vapor was added.

Study of the effects of variations in pressure spanned the range of one to three atmospheres, and covered operation at both high and low space velocity.

e. Shut-Down Procedure

The shut-down proceeds in the following order:

(1) Shut off the fuel.

(2) After a few minutes (allowing time to burn all fuel remaining in the system) shut off the power to the various heaters.

(3) Take an oxygen reading on the feed mixture (without fuel).

(4) Shut off the air and take an oxygen reading on the N_2 or N_2 + CO_2 mixture. These oxygen readings (Steps 3 and 4) are made to check on the composition of the gases fed during the run, and to check the calibration of the oxygen analyzer.

(5) Reduce flow of N_2 (to a total of about 4 ℓ/min) and shut-off CO_2, if used. This standby flow of nitrogen is left on overnight.

(6) Check oxygen analyzer if necessary.

7.2.4 Chemical Analyses Procedures

The chemical analyses carried out in this investigation fall into two categories: routine analyses made by operating personnel at the test location, and special analyses made in American Cyanamid's supporting Research Service Laboratories.

a. Routine Analyses

Oxygen in the reactor exit gas was monitored continuously, using a Beckman Model 777 in-line analyzer connected to a Honeywell Model Electronic 193 recorder, with a 0-100 mv span. This temperature-compensated instrument reads out directly in volume percent oxygen, and thus gives a continuous indication of the level of conversion when the inlet oxygen concentration is known.

Carbon dioxide levels in the reactor off-gas were measured by means of a simple gas chromatograph (Carle, Model Basic TM) coupled to a strip-chart recorder (Fisher Scientific, Model PWSN, 0-1 mv span). Intermittent samples for injection into the chromatograph were taken with a syringe through the CO_2 sampling port shown in Figure 24.

It was originally intended to determine carbon monoxide levels on a routine basis with the Carle gas chromatograph, but the column set up for this purpose proved insufficiently sensitive.

b. Special Analyses

Samples of reactor exit gas for various analyses carried out in supporting laboratory facilities were taken through the "vent and sampling port", using evacuated glass sampling bulbs of 200-1000 ml capacity. Several such samples were taken in most runs during periods of steady operation.

Analyses for CO, CO_2, O_2 and H_2 in the gas samples were carried out by gas chromatography. The instrument employed was the Hewlett-Packard Model 5750 Research Chromatograph.

Ultraviolet spectroscopy was used to check several samples of exhaust gas for the presence of SO_2, NO_2, and aromatic hydrocarbons. An Applied Physics Corporation Model Cary 11 instrument, and an 88.6 cm cell were used.

During runs in which water was added to the feed gases, samples of condensate were collected from the water trap located downstream of the reactor exhaust gas cooling coil. These samples were analyzed for nitrates, sulfates, and acidity; and for dissolved aromatics by uv spectroscopy.

7.3 Results and Discussion

A total of 24 experimental runs were made with duration ranging from 4 to 16 hours. The runs are listed in Table VII, which gives the highlights of the conditions used and information sought. Only two runs, 23 and 24, were made using a bed two inches thick; all other runs were made with a 1-inch bed of catalyst. The 1-inch bed thickness was chosen on the basis of the preliminary design studies as a reasonable balance between excessive pressure loss at greater thicknesses, and very large catalyst bed cross-sectional area requirements at lower thicknesses.

Runs 1-12 were made with the bed of catalyst resting directly on a support screen. Because it would facilitate a definition of the temperature profile at the exit plane of the bed, later runs were made using a 1/4 inch-thick layer of inert granular material between the catalyst and the support screen. Thus, TC 9 was located at the exit plane of the catalyst.

Most of the runs were made at space velocities of 300,000 hr^{-1} or 30,000 hr^{-1}. The higher value corresponds to operation at the maximum ballast gas demand (encountered during powered descent of the aircraft), while the lower value represents a reasonable "turndown" ratio from the maximum value, and is more than sufficient to provide the ballast gas required during other flight modes.

7.3.1 Reaction Studies

The reaction studies comprised the determination of the effects of the following parameters:

- Space velocity
- Initial oxygen concentration
- Fuel/oxygen ratio
- Inlet temperature
- Presence of water vapor
- Bed thickness
- Pressure

Table VII: Summary of Experimental Runs

Run No.	Active Bed Length inches	Space Velocity hr^{-1}	Average Pressure psig	Diluents N_2	Diluents CO_2	Diluents H_2O	Inlet Oxygen Concentration Vol. %	Excess Fuel %	Comments
1-12	1	30,000-500,000	0-5	x	x	-	3-6	35-194	Exploratory runs. Use of furnace to aid in preheating caused radial gradients at inlet, reaction predominantly at walls.
13	1	300,000	1	x	x	-	5.6	0-194	Added preheat capacity. Fresh catalyst.
14	1	300,000	1	x	x	-	5.6	0-200	Studied effect of varying excess fuel at different inlet temperatures, high space velocity.
15	1	30,000	0	x	x	-	3.1	0-400	Studied effect of varying excess fuel at low space velocity.
16	1	30,000	0	-	-	-	21	Note	Simulated start-up.
17	1	30,000	0	x	x	-	3.0	0	Fresh catalyst.
18	1	300,000	1	x	-	-	5.7	0-100	Studied effect of water addition to feed gas.
			1	x	-	x	5.7	100	
			1	x	x	x	5.7	100	
			1	x	x	-	5.7	100	
19	1	300,000	41	x	-	-	5.7	10-100	Studied effect of pressure at high space velocity.
			41	x	-	x	5.8	0-10	
20	1	30,000	38	x	-	-	3.2	100	Studied effect of pressure at low space velocity.
			0	x	-	-	3.2	100	
21	1	300,000	40	x	-	-	5.7	0	Varied the amount of water added to feed (5-10% by volume).
			40	x	x	x	5.7	0	
22	1	30,000	36-40	-	-	-	21	Note	Simulated start-up under pressure.
23	2	300,000	40	x	x	-	5.3	0	Fresh catalyst. Studied effect of pressure in 2" bed.
			18	x	x	-	5.3	0	
			5	x	x	-	5.3	0-67	
24	2	30,000	40	x	x	-	3.5	0-50	Studied effect of water at low space velocity.
			40	x	x	x	3.5	50-100	

Note: *In simulated start-up runs, an attempt was made to maintain the inlet fuel concentration at 0.2-0.3% by volume (stoichiometrically equivalent to about 3-4.5% O_2).*

on conversion (of oxygen), temperature rise (Δt) and hot spot temperature, pressure drop (Δp), and reaction rate constant (K).

a. Reaction Kinetics

The rates of processes occurring in plug flow reactors frequently reflect the law of mass action; that is, they show a dependency on the concentration of one or more of the reactants. If the overall rate is directly proportional to the concentration of one reactant, the reaction process is described as first-order and, assuming constant volume, the following rate equation applies:

$$K = SV \ln \left(\frac{1}{1-X}\right)$$

where K is the reaction rate constant and other terms are as defined below. As shown in a previous study *, K is also defined by the Arrhenius equation

$$K = Ae^{-(B/T)}$$

where

K	=	reaction rate constant, hr^{-1}
SV	=	space velocity, hr^{-1}
X	=	conversion (fractional form)
A	=	frequency factor, a system constant
B	=	E/R = energy of activation/gas constant
T	=	absolute temperature in reaction zone

In the situation relevant here, such an equation is a great over-simplication since the temperature of the catalyst is non-uniform. However, it may be used as an approximation, with T taken as the hot spot temperature. A more appropriate description of the reaction kinetics is obtained by plotting conversion at various space velocities as a function of the hot spot temperature, as shown in Figure 26.

It should be noted in connection with Figure 26 that for SV = 30,000 hr^{-1} the initial concentration of oxygen (in the feed) was approximately 3%, while at all other space velocities it was about 6% by weight. The "band" for SV = 300,000 hr^{-1} contains the results for dry and wet (with water in the feed mixture) runs, at 0 and 40 psig, and for 1 inch and 2 inch bed thickness. Within this band, there were no apparent correlations among these latter variables.

*Report AFAPL-TR-69-68

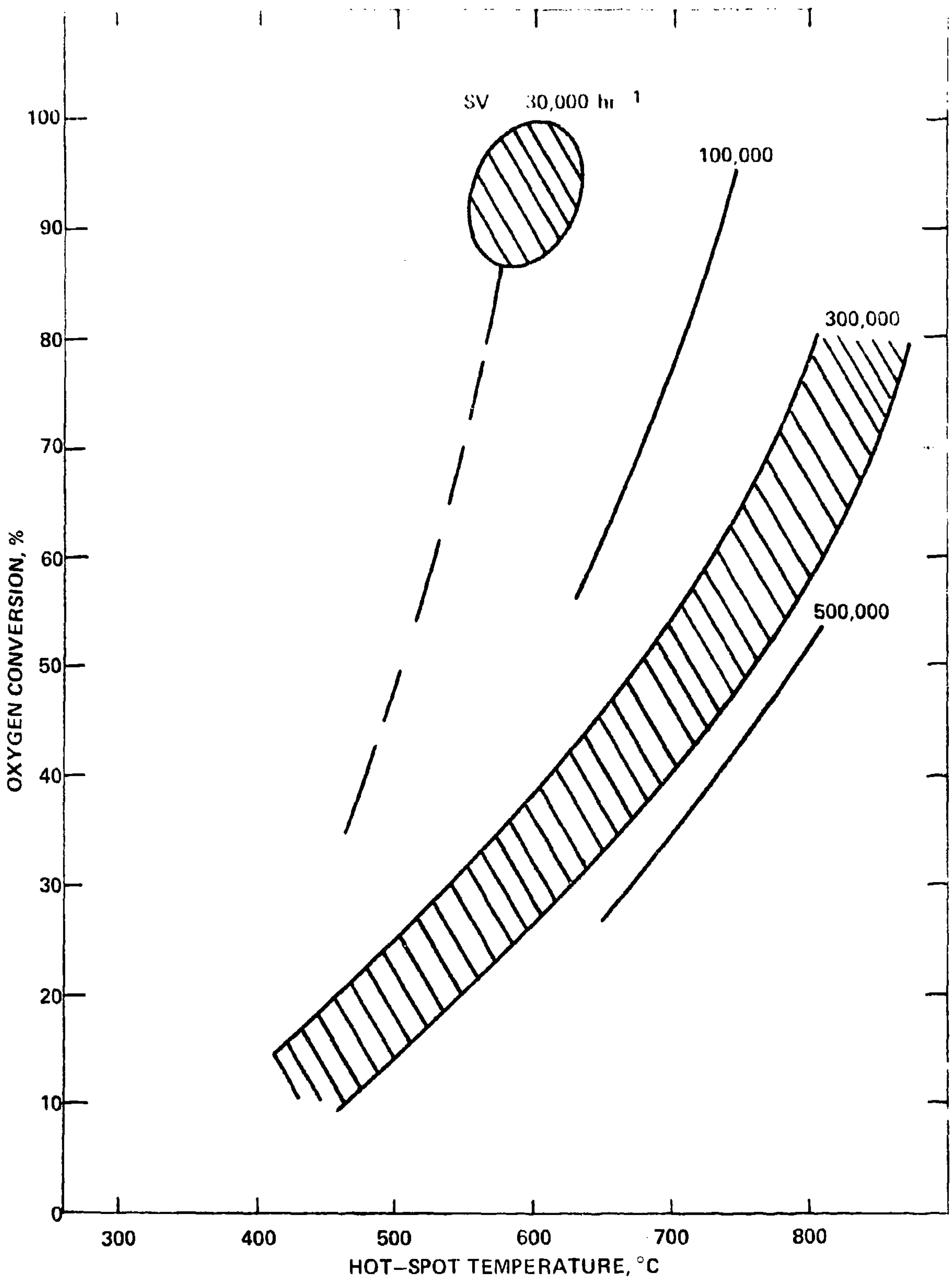

FIGURE 26 EFFECT OF SPACE VELOCITY AND HOT–SPOT TEMPERATURE ON CONVERSION

The data presented in Figure 26 may be used to test the rate expression previously given. Thus, for a temperature of 725°C, and using the range of values within the band at SV = 300,000 hr^{-1}, the following values for the reaction rate constant may be calculated:

SV, hr^{-1}	K_{725}, hr^{-1}
100,000	190,000
300,000	175,000-260,000
500,000	240,000

These values, while not remaining entirely constant with varying space velocity, do indicate that the value of 194,000 hr^{-1} used in the preliminary design analysis is reasonable, and may be used conservatively for space velocities in the neighborhood of 300,000 hr^{-1}.

At 30,000 hr^{-1} space velocity, as conversion approaches 100% calculation of the rate constant becomes less meaningful. The preliminary design calculations, based on the K value of 194,000 hr^{-1} at 725°C, predicted that conversion would approach 100% at 300,000 hr^{-1} space velocity. This prediction appears conservative, since the experimental data showed conversions approaching 100% at hot-spot temperatures of about 600°C.

b. Operation Under High-Flow Mode

This mode represents operation during normal powered descent, when the ballast gas demand is at a maximum. To conform with the preliminary design analysis, tests simulating this mode of operation were carried out at a space velocity of 300,000 hr^{-1} with an inlet concentration of approximately 6% by weight.

(1) Temperature Rise

The experimentally observed temperature rise is shown as a function of conversion in Figure 27, together with the calculated relationship for an adiabatic reactor. It is readily seen that the reactor is quasi-adiabatic for most situations up to a conversion level of 40-50%. An apparent departure from the adiabatic line was noted in the one "wet" run at atmospheric pressure. This may indicate a possible shift toward less exothermic reactions (steam reforming and decoking reactions are endothermic), but

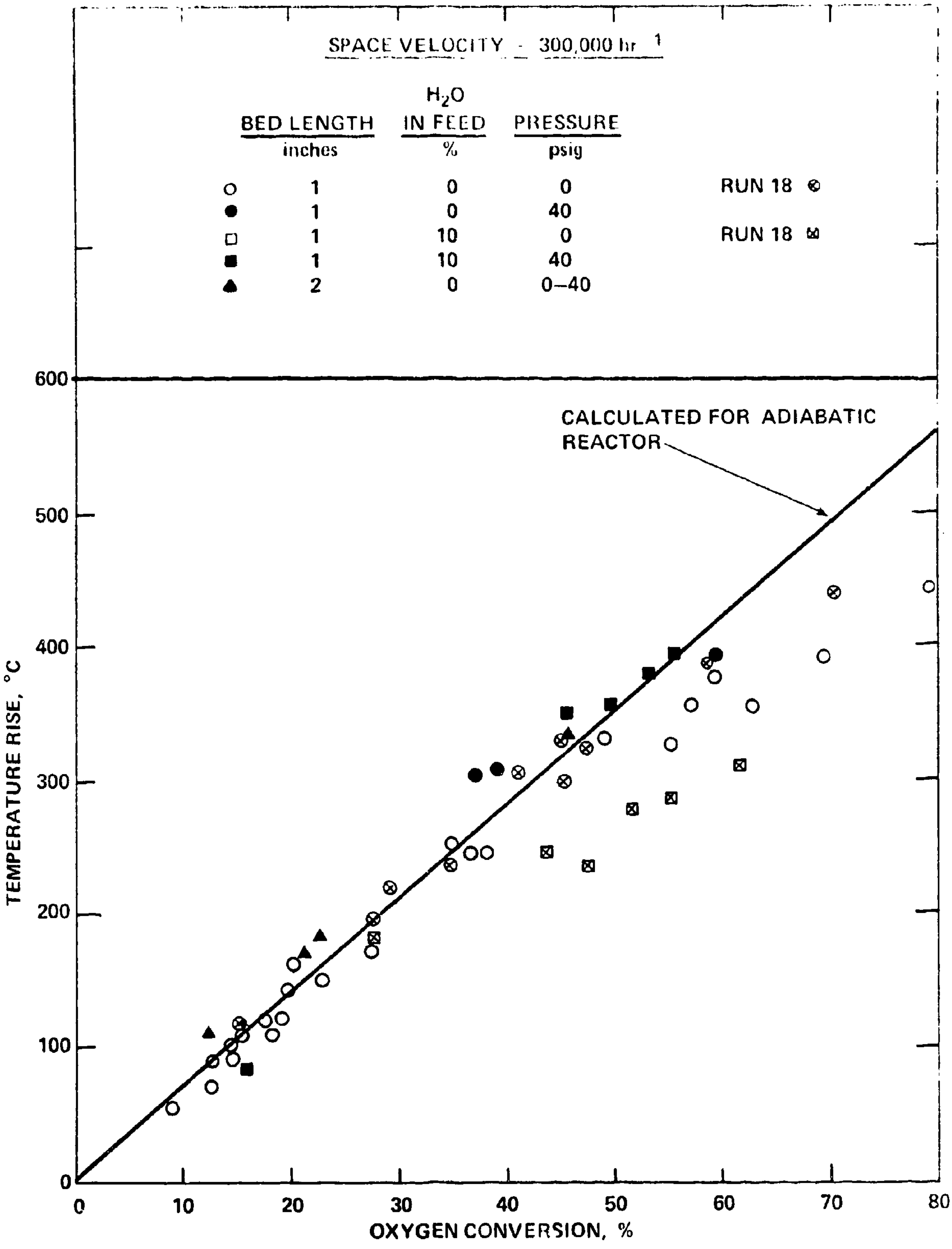

FIGURE 27 TEMPERATURE RISE VS CONVERSION

there was little direct chemical evidence for such a hypothesis (see following section on effect of excess fuel).

(2) Temperature Profiles

Figure 28 illustrates typical axial temperature profiles observed within the catalyst bed at 300,000 hr^{-1} space velocity. Temperatures at the entrance plane range from 375° to 400°C in all cases. For a bed thickness of 1 inch, the highest temperature was achieved at the exit edge of the bed. The profile was similar in the 2-inch bed, but leveled off in the last 1/4 inch of the catalyst.

It should be noted that in addition to the axial gradients there were also radial temperature gradients, amounting in the 1 inch bed to 10-20°C near the bed entrance, and to 125-150°C near the exit plane (for hot spot temperature in the neighborhood of 700°C).

(3) Effect of Excess Fuel

Figure 29 indicates the effect of excess of fuel on the inlet temperature required to reach a given conversion when operating at a space velocity of 300,000 hr^{-1} and at atmospheric pressure. There is clear evidence of the beneficial effect of fuel excess (over stoichiometric requirements) on the reaction rate. At the same time it is also evident that the higher the excess of fuel, the more precise is the control of inlet temperature required to maintain the desired conversion and prevent overheating of the catalyst.

The effect of excess fuel was not studied in detail at pressures above atmospheric because of time limitations. In one run at 40 psig, however, increasing the fuel from stoichiometric to an excess of 10-35% produced significant increases in conversion (from about 40% to 60%) with little change in inlet temperature.

(4) Effect of Water Vapor in the Feed

The shift that takes place upon inclusion of water vapor in the feed is indicated in Figure 30. It is evident that at 40 psig, as well as at atmospheric pressure, the inlet temperature in a "wet" run must be higher than in a dry run to achieve the same level of conversion. This must be taken into account in planning an operational unit, where water vapor will be present in all situations except the first bed during startup.

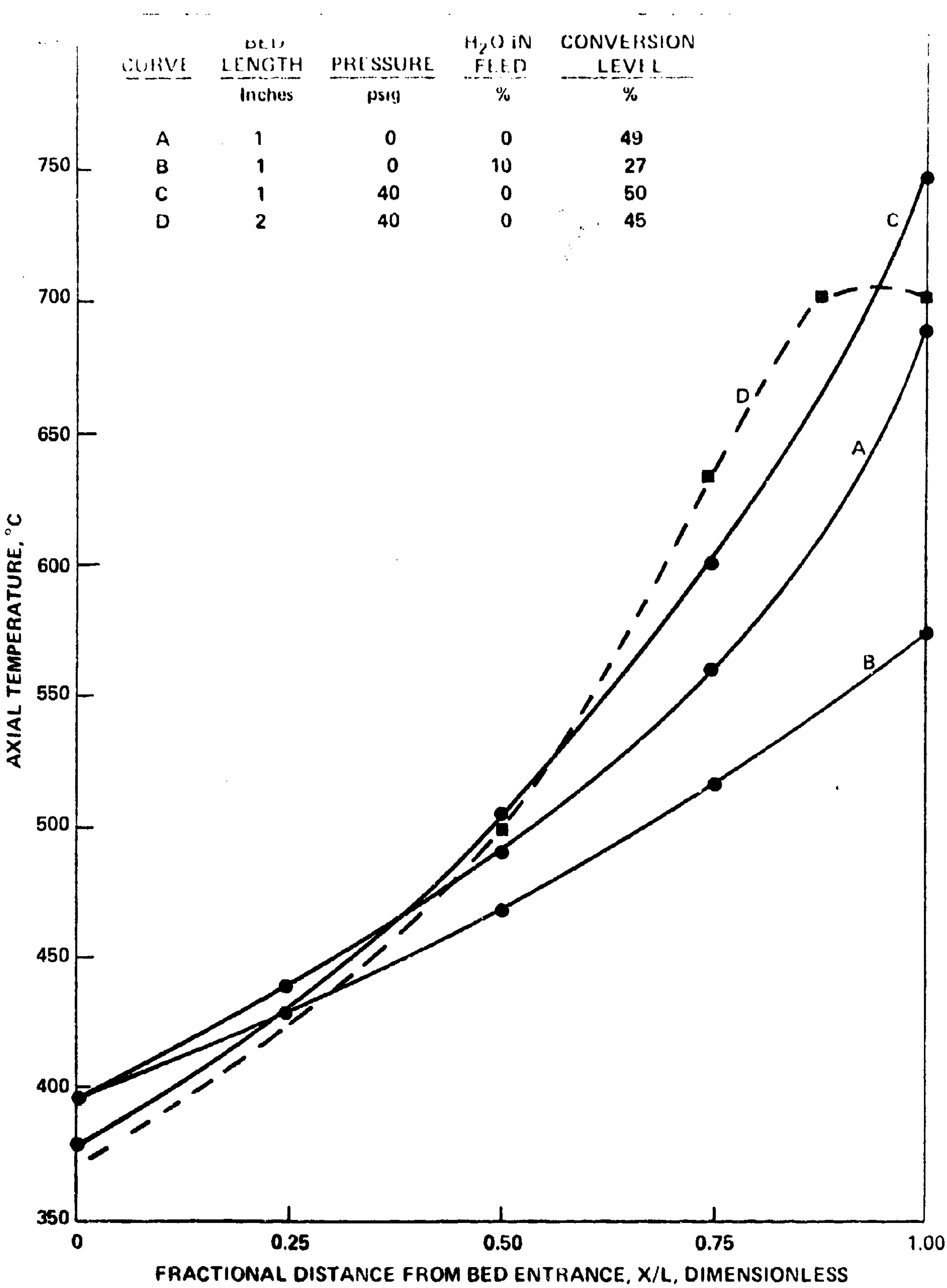

FIGURE 28 TYPICAL TEMPERATURE PROFILES SPACE VELOCITY – 300,000 HR^{-1}

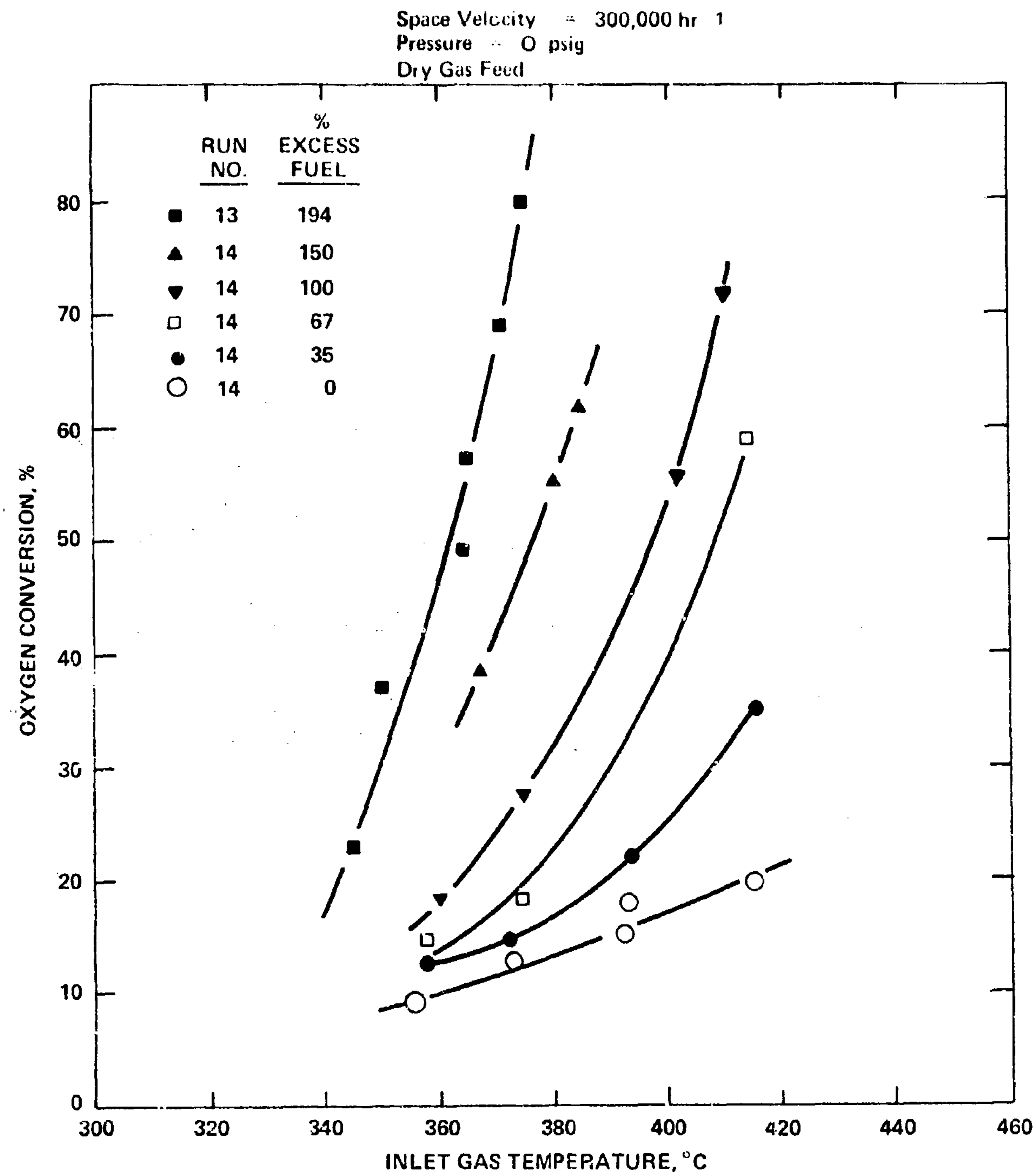

FIGURE 29. EFFECT OF EXC[illegible] FUEL

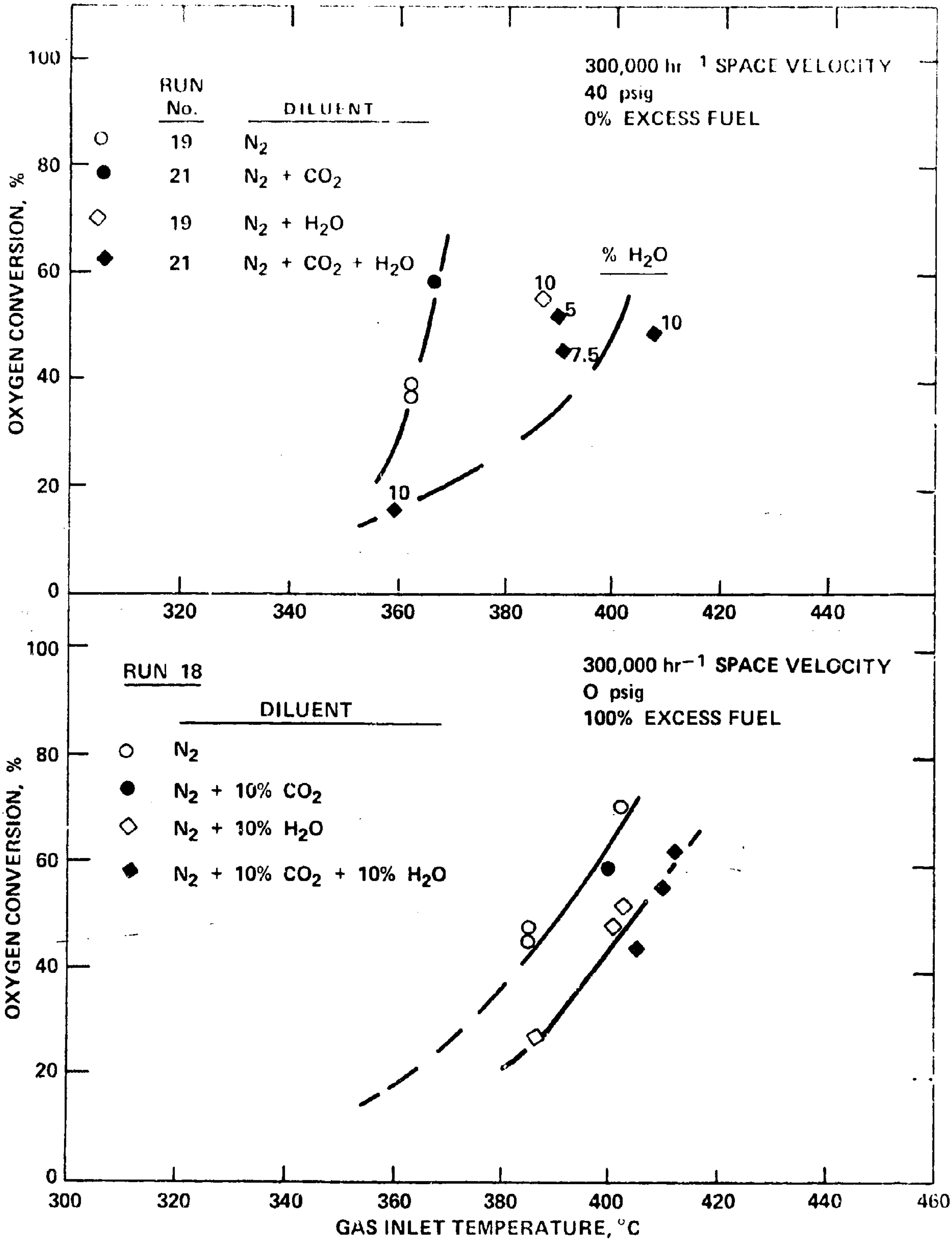

FIGURE 30. EFFECT OF WATER ADDITION TO FEED GAS

Unfortunately, time did not permit experimentation with levels of excess fuel other than those shown in Figure 30, or a definitive study of the magnitude of the effect of water as a function of water vapor concentration. Data from Run 21 do indicate, however, that inlet temperature must be increased to maintain conversion as the water level in the feed is increased in the range of 5-10 volume percent.

(5) Effect of Pressure

The effect of pressure has already been touched upon in the preceding discussion of the effects of excess fuel and of water vapor. Reference to Figures 29 and 30 indicates that under otherwise identical conditions, a significantly lower inlet temperature is required to achieve a given conversion level at 40 psig than at atmospheric pressure. Some additional data were obtained during run 23, using a 2-inch bed of catalyst. In this run, conversion dropped from about 45% to 12% as the average pressure in the reactor was reduced from 40 psig to 7 psig, while maintaining a stoichiometric flow of fuel.

(6) Transient Behavior

A systematic study of the transient response of the experimental reactor to changes in operating variables (flow rate, inlet temperature, pressure, etc.) was not within the scope of the present program. It was thought to be of interest, however, to show a typical experimental "light-off" as an example of the transient behavior of the system. Figure 31 shows such a light-off, at SV = 300,000 hr^{-1}, 40 psig, and a stoichiometric fuel rate.

The figure shows that, following initiation of the reaction at about 345°C, temperatures within the bed rose gradually over a period of 20-25 minutes. Conversion rose correspondingly during this time, reaching about 50-55% after 20-25 minutes. Actually, due to feedback of heat along the walls of the reactor, the inlet temperature was increasing slowly, and a true "steady-state" was not reached.

The rate of temperature rise during light-off will depend on the particular set of conditions. For example, in several cases involving light-off at atmospheric pressure in the presence of excess fuel, hot-spot temperatures as high as 900°C were reached

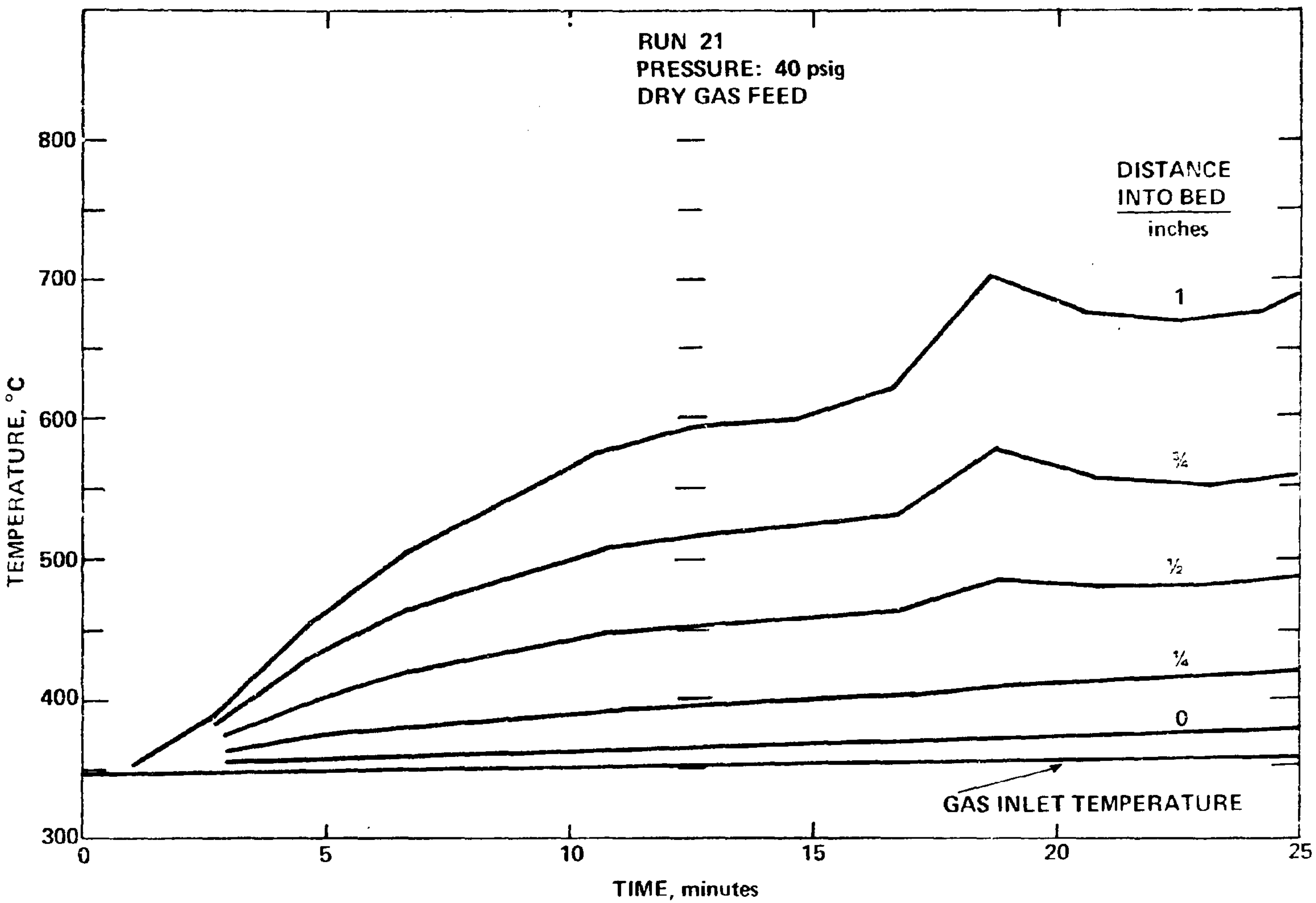

FIGURE 31 TYPICAL "LIGHT–OFF" AT 300,000 HR^{-1} SPACE VELOCITY

within about five minutes. The light-off illustrated in Figure 31 may well have proceeded faster if the inlet temperature had been higher, or if excess fuel had been used. Since these conditions would also lead to higher conversions, it would be necessary to take corrective action as the bed temperature approached the allowable maximum.

c. Operation Under Low-Flow Mode

This is the operation during cruise, at SV = 30,000 hr^{-1}, with the reactor feed containing approximately 3% by weight of oxygen. Table VIII summarizes most of the experimental data relating to this mode of operation.

(1) Temperature Rise

For the low-flow mode, the calculated temperature rise for 100% conversion is approximately 360°C (assuming an inlet 0_2 concentration of 3.2 weight %). Since the experimental data yielded lower values than the calculated, it appears that at 30,000 hr^{-1} space velocity heat losses from the experimental reactor are significant.

(2) Temperature Profiles

The temperature profiles at low space velocity (Figure 32) show that the hot spot is normally located in the upstream portion of the bed. At atmospheric pressure, there is a "hot-region" rather than a "spot", which indicates that a larger portion of the bed may be involved in the reaction. Under pressure, the hot spot typically appears very early in the bed.

In these low space velocity runs, depending on the temperature profile, radial temperature gradients of 100°C or more were observed near the bed as well as at the exit.

(3) Effect of Excess Fuel

As in the case of high space velocity, an excess of fuel at atmospheric pressure tends to lower the inlet temperature required to achieve a given conversion. With the feed entering at about 300°C and with 400% excess of fuel, a conversion of about 90% was achieved. With 0-100% excess, at 0 psig, the inlet

TABLE VIII

EFFECT OF INLET TEMPERATURE AND PRESSURE ON CONVERSION AT SV 30,000 HR^{-1}

Run No.	Inlet Temperature °C.	Pressure, psig	Excess Fuel %	Water Vapor in Feed, Vol. %	O_2 in Exhaust Gas, Vol. %	Conversion, %	Δt(1) °C
15	280-290	0	0-400	0	-	~0	-
15	292	0	300	0	~2.7	~8	-
15	305	0	400	0	~ 0.3	90	265
15	325-330	0	0-400	0	0.35-0.15	88-95	290
15	350-355	0	0-400	0	~ 0	~100	255
17	302	0	0(2)	0	~ 0.4	~85	285
20	246	40	100	0	-	~ 0	-
20	275	40	100	0	~2.8	~10	-
20	281	40	100	0	~0	~100	305
20	~300	0	100	0	~0.1	~ 95	285
20	305	0	0(2)	0	~0.2	~ 93	315
24(3)	314	40	0(2)	0	~1.25	40	162
24	320	40	50	0	~0	~100	332(4)
24	346	40	100	11	~0	~ 100	322(4)
24	354	40	50	11	~0	~ 100	353(4)

(1) Between hot-spot and inlet (axial).

(2) Stoichiometric

(3) 2-inch bed

(4) May not be the maximum.

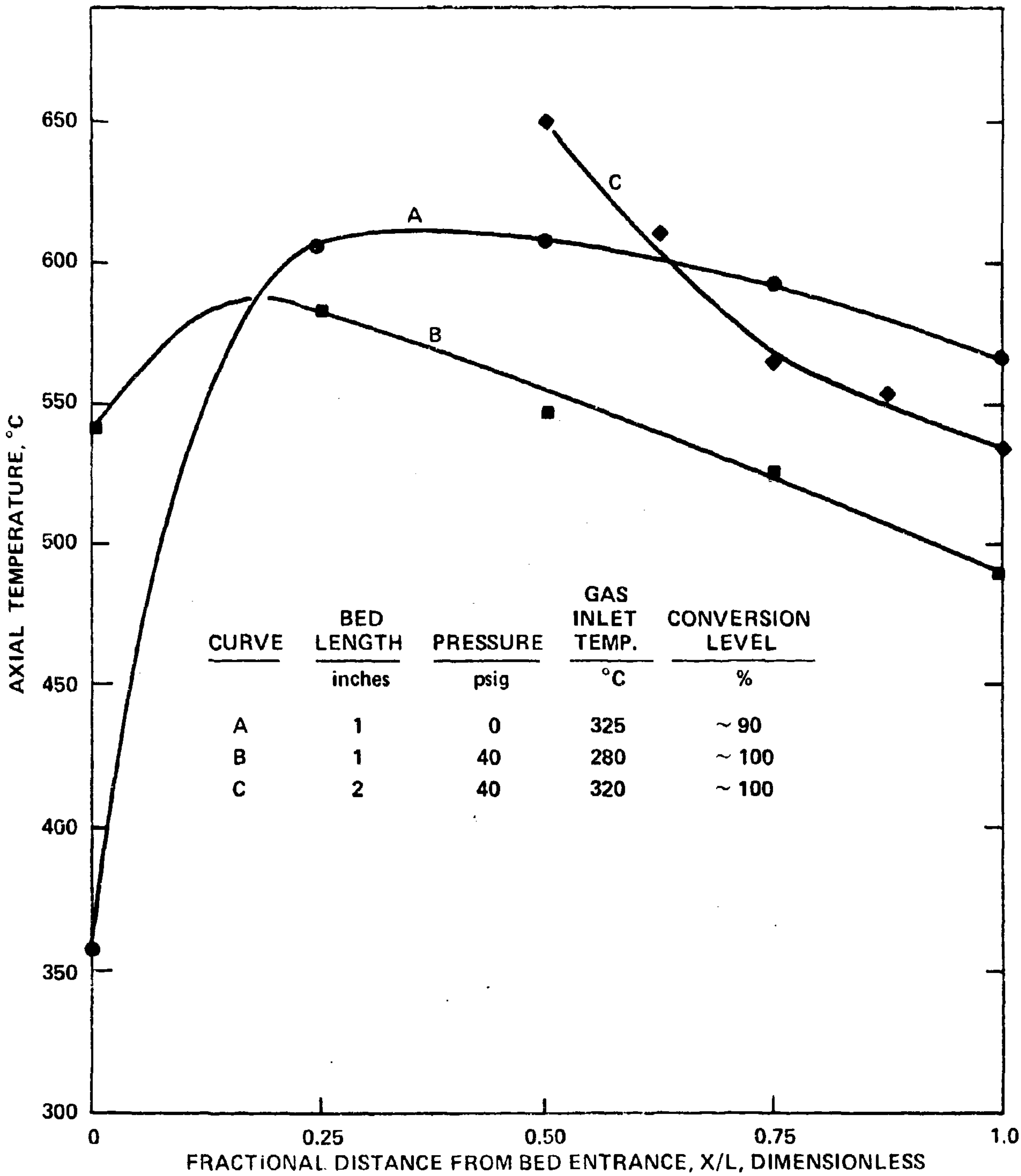

FIGURE 32 TYPICAL TEMPERATURE PROFILES
SPACE VELOCITY – 30,000 HR^{-1}

temperature must be 325-300°C to achieve 90% conversion, while if it is 350-355°C essentially 100% conversion is obtained. Table VIII summarizes the available information.

(4) Effect of Water Vapor in the Feed

Only one run (24) was made with water vapor in the feed, and it was found that approximately 100% conversion is obtained at 40 psig with the feed entering at about 350°C, and containing 50-100% excess of fuel, in the 2-inch bed. Since conversions approaching 100% might have been achieved at lower inlet temperatures had they been run, the effect of the water addition is not clearly defined by the data from this run.

(5) Effect of Pressure

The data from run 20 indicates that pressure tends to lower the inlet temperature required for high conversion at low space-velocity. Thus, at 40 psig and 100% excess fuel, an inlet temperature in the vicinity of 280°C is sufficient to achieve almost 100% conversion, while temperatures above 300°C are required at atmospheric pressure.

(6) Transient behavior of the reactor at low space velocity (30,000 hr^{-1}) are given in Figures 33 to 35. Figures 33 and 34 show "light-offs" under two different sets of conditions, with markedly different transient behavior. Figure 35 shows a loss of reaction ("flame-out") resulting from a slow decrease in the inlet gas temperature.

A fast light-off is illustrated in Figure 33. In this case, operating at atmospheric pressure, the stoichiometric rate of fuel was introduced when the inlet gas temperature was at 315°C. In slightly more than two minutes, 90% conversion was obtained, while the temperature at all points in the bed rose essentially simultaneously. During the period of time shown in the figure, the inlet temperature rose to 323°C and the hot-spot moved deeper into the bed (from 1/4 to 1/2 inch).

A "slow" light-off (Figure 34) was obtained at 40 psig, with 100% excess fuel and initial inlet temperature of 273°C. The conversions were as follows (referring to the figure):

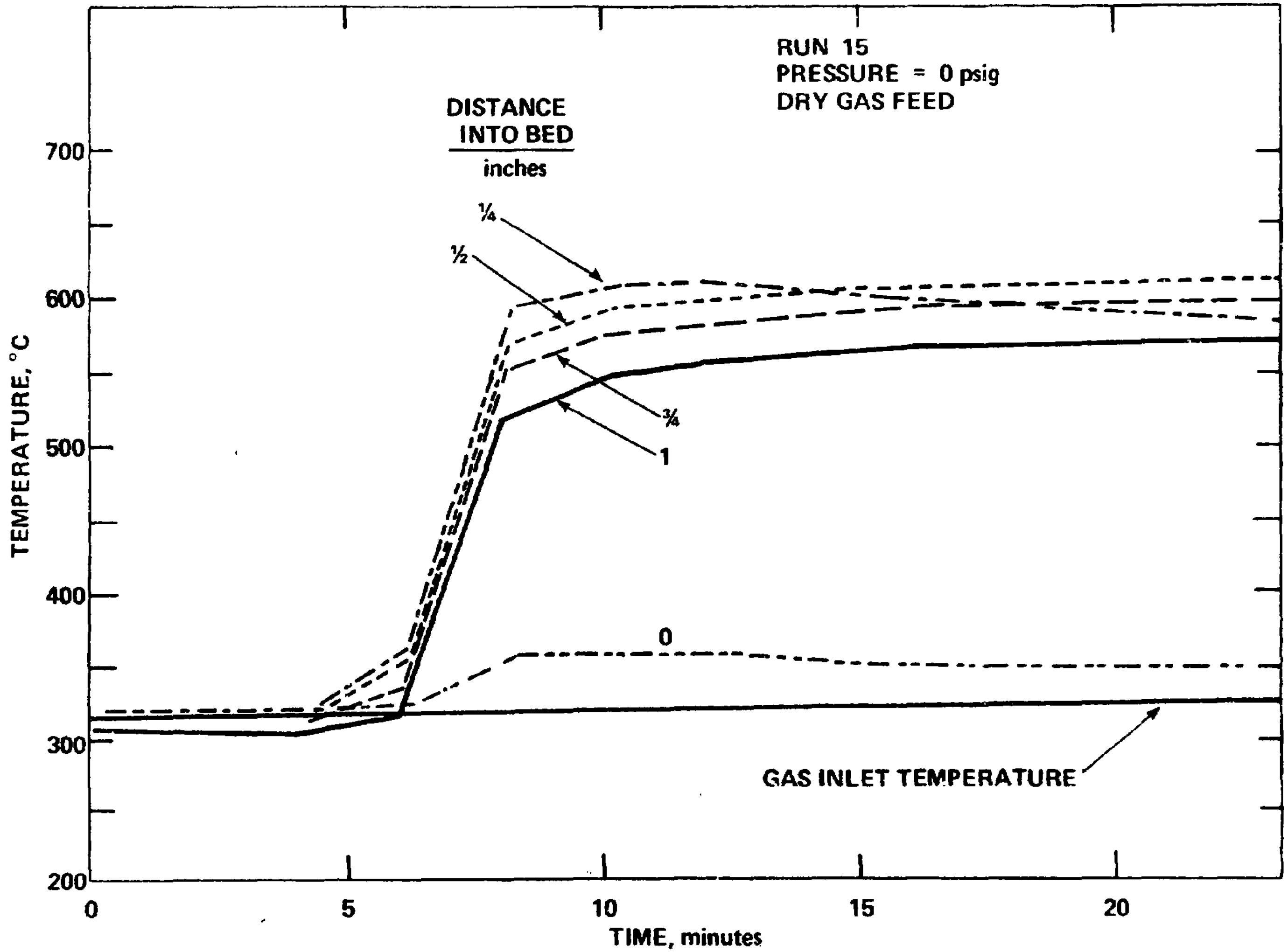

FIGURE 33 RAPID "LIGHT-OFF" AT 30,000 HR^{-1} SPACE VELOCITY

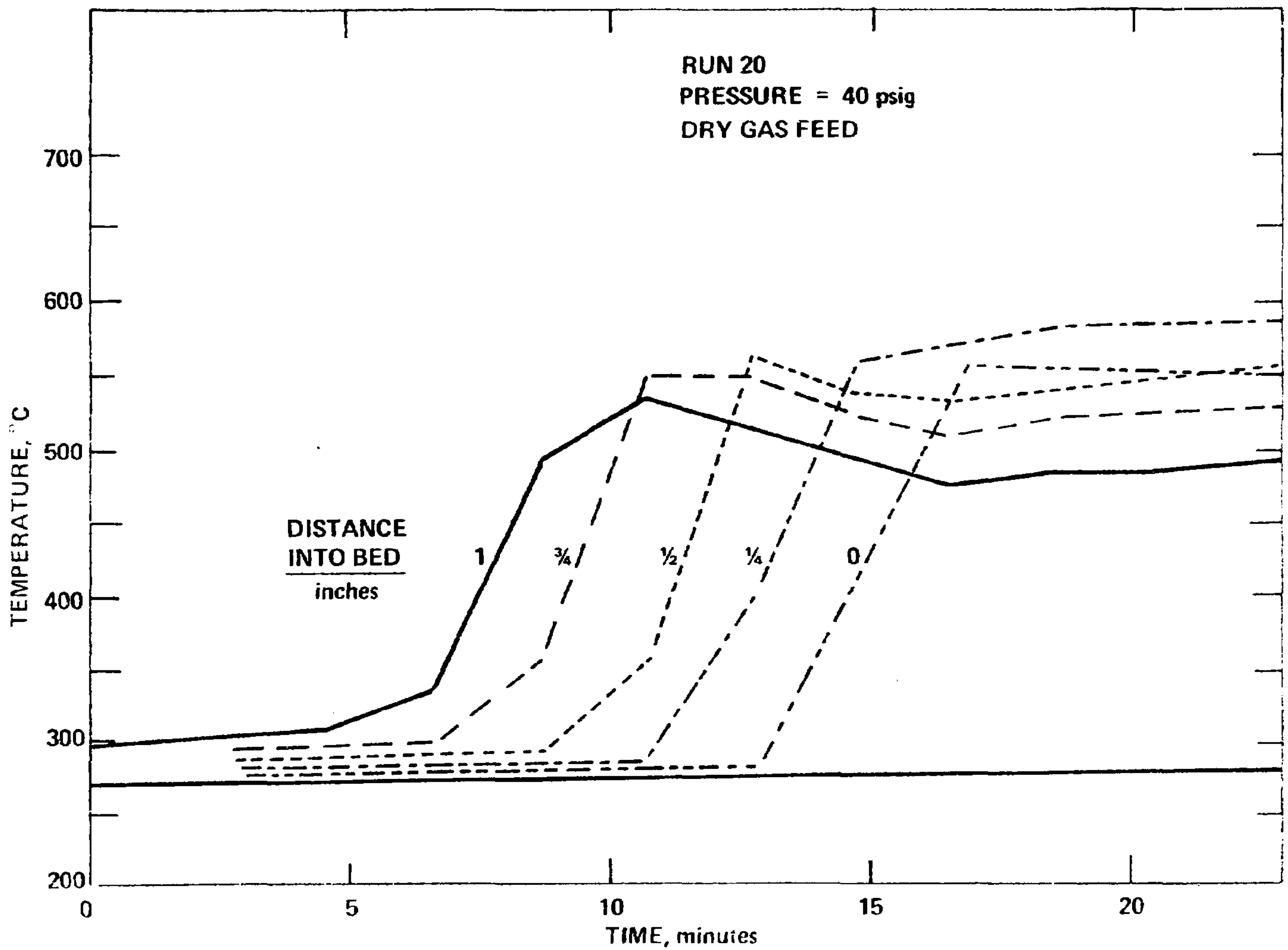

FIGURE 34 SLOW "LIGHT-OFF" AT 30,000 HR^{-1} SPACE VELOCITY

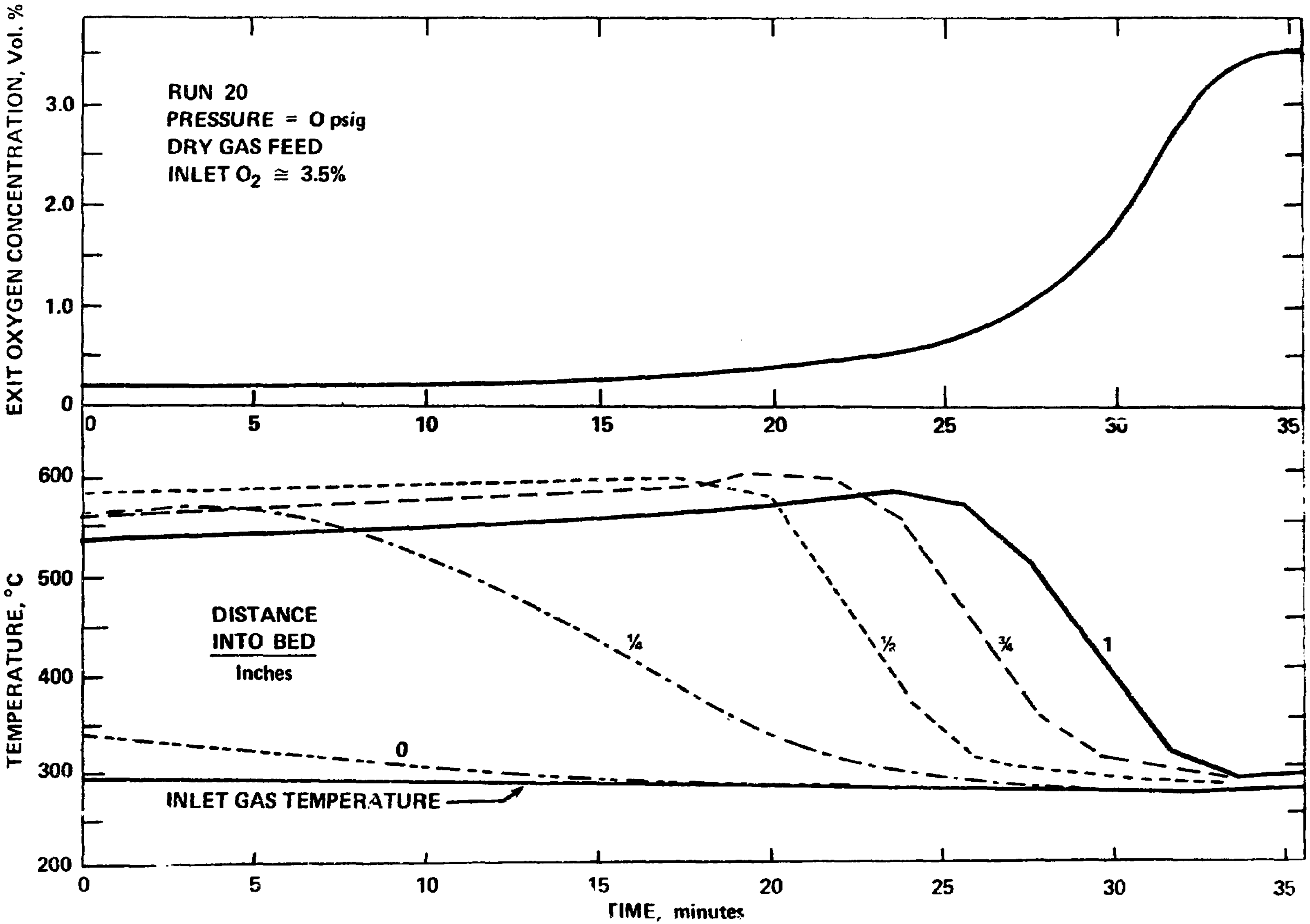

FIGURE 35 LOSS OF REACTION AT 30,000 HR^{-1} SPACE VELOCITY

Time Elapsed, min.	Conversion, %
0	0
5	10
7	14.5
9	47
11	84
13	95
15	98

During this period of time, the location of the hot spot moved from the exit edge of the bed to a point 1/4 inch from the bed entrance. The temperature at the different points in the bed rose in succession, starting with the farthest downstream, and even the temperature at the entrance edge finally rose sharply. The inlet gas temperature rose slightly to about 280°C during the light-off period.

A reverse transition, representing a loss of reaction ("flame-out") due to an induced drop in inlet temperature is shown in Figure 35. While the inlet temperature was dropping slowly from 294°C to 275°C, the "hot region" was moving slowly downstream in the bed. Temperature at the different points within the bed dropped off in reverse order to that shown for the slow light-off in Figure 35. As long as the hot spot was within the bed, very little loss in conversion was observed, as can be seen from the oxygen concentration curve. Once it reached the exit edge of the bed, however, the oxygen level rose rapidly. This loss of reaction preceeded slowly as the inlet temperature was slowly decreased. A more rapid decrease in inlet temperature would undoubtedly have given a more rapid response.

d. Start-Up Simulation

Two attempts were made to simulate the start-up operation at SV = 30,000 hr^{-1}, one at atmospheric pressure, and one at 40 psig. In both cases, undiluted air and small amounts of fuel were fed to the experimental system. It was intended to keep the fuel-vapor concentration low in order to stay below the lower flammability limit, as well as to limit the temperature rise to the maximum permissible value:

0.2% fuel vapor   3% O_2 14.3% conversion   410°C Δt

Trouble was experienced with controlling such small flow rates of fuel, however, especially in the pressure run, and in both runs exotherms carrying the bed temperature over 1000°C occurred.

In the atmospheric pressure run, no reaction was observed below 280°C, but with inlet temperatures in the range of 300-310°C, an exotherm to about 530°C was obtained. Increasing the inlet temperature to 325° resulted in an excessive temperature rise (hot-spot over 1000°C) and deactivation of the catalyst. In the pressure run, a high exotherm was encountered when the inlet temperature was only 230°C. In this case, the oxygen level in the air was reduced by the reaction to about 2.5%, so that a large excess of fuel over that intended must have been inadvertently fed. In the same pressure run, the space velocity was increased to 100,000 hr^{-1} and the inlet temperature to about 330°C. Under these conditions, a moderate exotherm (to about 540°C) and about 10-15% conversion of the oxygen in the air was observed at a fuel concentration of 0.2 volume %.

The above data are too meager to give an adequate definition of light-off requirements in air, but they do suggest that the inlet temperatures needed may not differ greatly from those observed when the inlet oxygen concentration was 3%.

7.3.2 Pressure Drop

The relationship used in the design analysis to estimate the pressure drop due to passage of gases through a bed of catalyst is given by

$$\Delta P = 0.0014 \left(\frac{T_{ave}}{P_{ave}}\right)(SV \times 10^{-5})^{1.85} (1)^{2.85} A_f$$

where:

ΔP	=	pressure drop, psi
T_{ave}	=	average absolute temperature in bed, °R
P_{ave}	=	average absolute pressure in bed, psia
SV	=	space velocity, hr^{-1}
1	=	bed thickness, inches
A_f	=	wall factor (dimensionless)

The validity of this relationship has been confirmed experimentally, both at room temperature (Figure 36) and under reaction conditions (Table IX). The data presented in Figure 36 were obtained at essentially atmospheric pressure, but because the pressure drop through the bed was considerable at the higher flow rates used it was necessary to correlate the data on the basis of the product of the average pressure and the pressure drop. A slightly different value for the constant in the general relationship was used in this case, to account for the different physical properties of nitrogen at room temperature, as compared with those of the gas mixture at reactor conditions. The wall factor was taken as 0.76, based on a relationship involving average particle size and reactor diameter given in the literature.

It may be seen from Figure 36 that there is excellent agreement between the experimental and the predicted values for the 2 5/16-inch bed thickness. For the smaller beds, the fit of the data is somewhat poorer but still satisfactory.

In Table IX, the pressure drops observed during actual reactor runs are compared with the predicted values, for space velocities ranging from 100,000 to 500,000, and for pressures from ambient to 56 psia. Here again, the agreement between the calculated and observed values is good, with the observed values generally running about 10-20% higher.

7.3.3 Chemical Analysis Data

The relative amounts of CO_2 and CO in the reactor exhaust stream are of interest not only from the environmental standpoint, but also as an aid to interpreting the effects of operating variables on the reaction mechanisms. Samples from a number of experimental runs were therefore analyzed by gas chromatography for these constituents, as well as for hydrogen. The results are summarized in Table X.

CO levels in the various samples tested ranged from about 0.1 to 0.8%. Some caution must be exercised in interpreting the results given here, because in many cases, the "oxygen balance" does not check well. If the only major reactions occurring involve oxidation of the fuel to CO, CO_2 and H_2O, then 1.5 mols of O_2 are accounted for by each mole of CO_2 ($+H_2O$) formed, and 1.0 mols O_2 for each mole of CO ($+H_2O$). Thus, the CO formation plus 1.5 times the net CO_2 formation should equal the oxygen disappearance. Net CO_2 formation is best indicated in those runs in which there was no CO_2 in the feed. For three such situations in the table, only one (Run 21) gave a reasonably close oxygen balance.

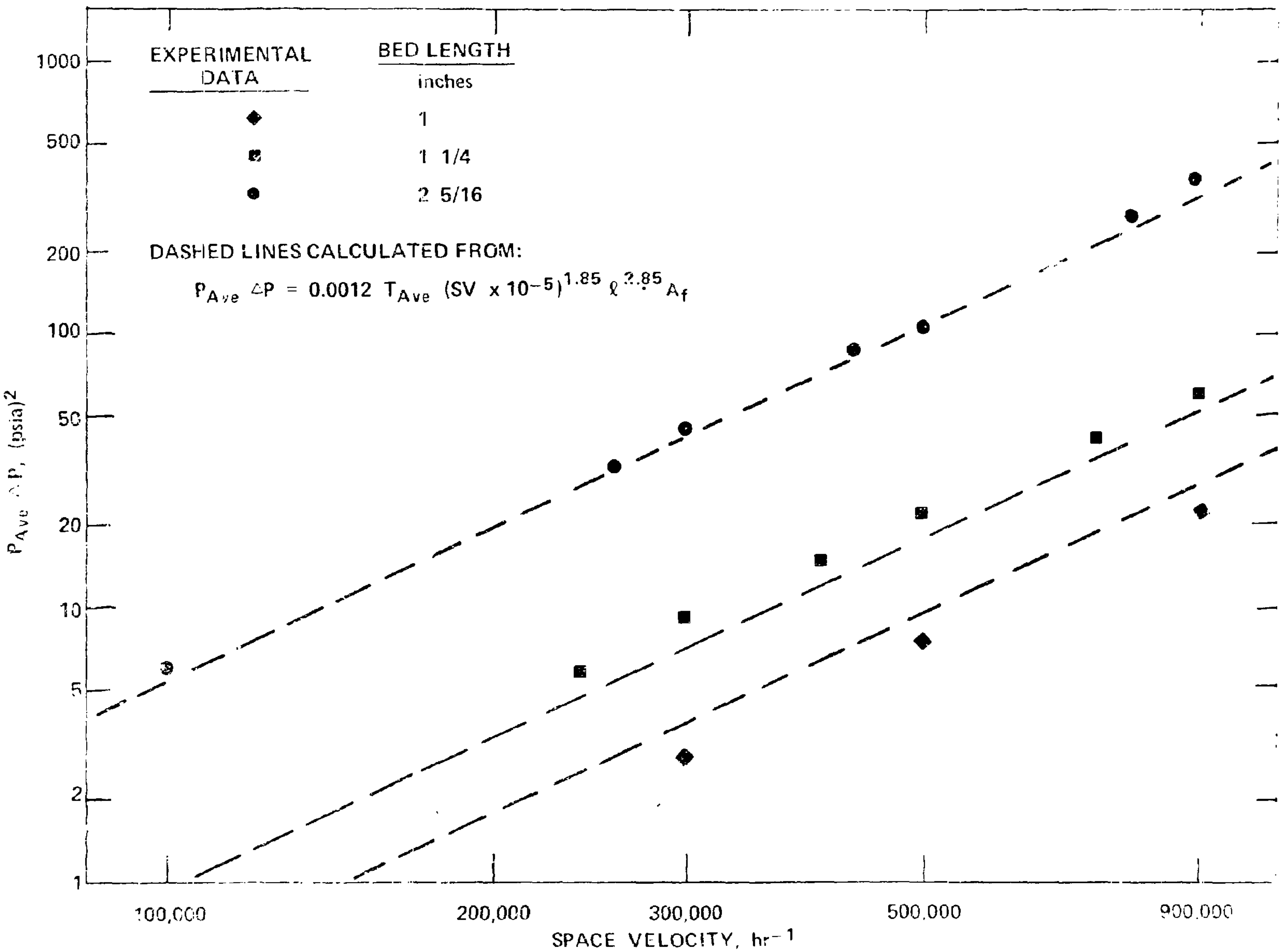

FIGURE 30 PRESSURE DROP DATA
GAS FEED. NITROGEN AT ROOM TEMPERATURE

TABLE IX: PRESSURE DROP DATA AT REACTOR CONDITIONS

Bed Length inches	Space Velocity(1)	Average Bed Temperature(2) °F	Average Bed Pressure psia	Pressure Drop, psi Calculated(3)	Observed(4)
1	100,000	995	14.8	0.10	0.15
1	300,000	1000	16.2	0.74	0.8-0.9
1	500,000	1010	18.5	1.65	2.0
1 1/4	240,000	970	16.2	0.92	0.9-1.0
2 5/16	259,000	965	55.7	1.77	2.0
2 5/16	259,000	1025	21.6	4.75	5.1

(1) Space velocity based on catalyst plus inert packing.

(2) Arithmetic average of inlet and outlet gas temperatures.

(3) Calculated from:

$$\Delta P = 0.0014 \, (T_{ave}/P_{ave}) \, (SV \times 10^{-5})^{1.85} \, (\ell)^{2.85} \, (A_f)$$

where A_f = wall effect factor, taken as 0.76 in 1" diameter bed.

(4) Difference between Δ P observed during run and blank reading under same conditions but without catalyst bed.

TABLE X: GAS CHROMATOGRAPHIC ANALYSES OF REACTOR EXIT GAS

Run No.	Space Velocity, hr^{-1}	Pressure, psig	Diluent N_2	Diluent CO_2	Diluent H_2O	Analysis, Vol. % O_2[1]	CO_2	CO	H_2
2	300,000	0	x	x		2.6	13.8	0.80	0.02
14	"	0	x	x		2.5	8.7	0.76	0.05
14	"	0	x			2.6	2.5	0.77	0.03
18	"	0	x			3.3	-	0.65	0.02
18	"	0	x	x	x	2.6	11.6	0.57	0.03
18	"	0	x	x	x	2.2	11.7	0.74	0.04
18	"	0	x		x	3.0	1.09	0.46	0.02
23	"	40	x	x		2.9	10.9	0.12	0.01
21	"	40	x	x		3.0	12.4	0.45	0.02
21	"	40	x			2.3	1.97	0.34	0.01
23	"	9	x	x		2.7	9.1	0.37	-
15	30,000	0	x	x		0.4	13.1	0.19	0.02
17	30,000	0	x	x		0.6	10.4	0.35	0.03
Feed[2]	300,000	-	x	x		5.3-5.8	8.1-9.0	-	-
Feed[3]	30,000	-	x	x		3	12.0	-	-

(1) Beckman O_2 Analyzer

(2) Range for 5 samples.

(3) One sample.

Keeping these reservations with regard to the accuracy of the data in mind, some tentative conclusions may still be drawn. For the dry runs at high space velocity, it appears that C0 formation accounts for about 25-30% of the oxygen disappearence. With water added, somewhat less C0 (about 20% of the 0_2 disappearance) may have been formed. For the runs under pressure, and at low space velocity, C0 formation appears to be significantly lower, on the order of 5-15% of oxygen disappearance.

The possibility of <u>hydrogen</u> formation through shift or reforming reactions is of interest because of possible problems involving embrittlement of structural equipment. Since these reactions are considerably slower than the oxidation reactions, it was not expected that they would occur to any appreciable extent. As indicated in Table X, however, small quantities of hydrogen were detected in virtually all of the samples. No correlation with reaction conditions is evident.

The JP-4 fuel used in this test program contains appreciable <u>sulfur</u> (0.165%). The fate of this sulfur is of interest because of potential corrosion problems in downstream equipment. Complete oxidation of the sulfur contained in the stoichiometric quantity of fuel required for an inlet oxygen concentration of 6% would result in an $S0_2$ concentration of about 25 ppm in the reactor exhaust. In samples from dry and wet runs, both at atmospheric pressure and at 40 psig, no $S0_2$ was detected by UV spectroscopy (limit of detection about 20 ppm). Condensate samples collected during wet runs were found to be strongly acidic (pH 1.8-2.3), however, and to contain significant amounts of $S0_4{}^=$ (see Table XI).

An approximate calculation, based on the ratio of fuel to water fed, and assuming complete oxidation of the sulfur in the stoichiometric quantity of fuel, gives a value of about 0.16% $S0_4{}^=$ in the condensate. Thus, the analyses for the high space velocity runs in Table XI account for about half of the sulfur fed (the balance presumably passes through the system unreacted). The value for the low space velocity run seems unreasonably high, unless the excess of fuel was actually significantly greater than the indicated value.

TABLE XI: ANALYSES OF CONDENSATE SAMPLES

Run No.	Run Conditions			Analysis		
	SV hr^{-1}	Pressure psig	% Excess Fuel	pH	NO_3^- %	SO_4 %
18[(1)]	300,000	atm	100	2.1-2.2	.012	.16-.[illegible]
21	300,000	40	0	2.3	.013	.0[illegible]
24	30,000	40	50-100	1.8	.013	.94

(1) Two Samples

Nitrogen oxides were not detected in the reactor exhaust gas by UV spectroscopy (limit of detection about 20 ppm), although trace quantities of nitrates were detected in the condensate samples.

Further examination of the condensate samples, using UV and spectrofluorometric techniques, revealed the presence of water-soluble aromatic compounds. While these were not quantitatively determined or identified, they appeared to be principally benzene derivatives, with smaller amounts of naphthalenes and larger ring aromatics.

7.4 Areas for Further Study

While the experimental program carried out under the present effort has provided much useful data regarding the functioning of the catalytic reactor under conditions simulating actual operating conditions, there are still a number of areas in which information is sketchy and in which further investigation might profitably be carried out before proceeding with (or concurrently with) system studies involving a "breadboard" or prototype unit. In particular, the following areas need further study:

a. Interactions Among Operating Variables

The effect of excess fuel and water vapor concentration on the conversion versus temperature relationship at pressures above atmospheric needs to be studied in more detail.

b. Transient Behavior of the Reactor System

A thorough understanding of the response of the system to changes in level of the many operating variables - flow, temperature, pressure, excess fuel, etc. - is essential to successful operation of the catalytic inerting system. Further studies, both theoretical and empirical, would be desirable in this area.

c. Catalyst Stability

Very little data has been obtained to determine the life-expectancy of the catalyst under the projected operating conditions. A study of the factors affecting coke formation, and the effects of coking on catalyst performance would be desirable.

d. System Chemistry

A more thorough investigation of possible side reactions occurring during various modes of operation and of the effect of recycling partial combustion products would be of interest. Identification of the water-soluble aromatics noted in the current program might also be worthwhile.

e. Testing of Improved Catalysts

It seems likely that catalyst preparations providing improved pressure drop characteristics without loss in performance capabilities can be formulated. Testing of such improved catalysts, particulary for stability, would constitute an important area for further work.

Much of the information and testing described above could be carried out in the 1 - inch unit used in the current work.

8.0 PRELIMINARY DESIGN DEVELOPMENT AREAS

In several areas of the system design, the design has been completed recognizing that there is at this time insufficient data to support all of the approaches used. These areas represent items which must be investigated further in the follow-on experimental program. These areas are considered to represent some uncertainty in the design selected but, in general, any problem areas that are encountered in the experimental phase can be corrected by changes in system design. The experimental program must be directed at investigating these problem areas early in the course of the program so that corrective measures and design modifications can be incorporated where necessary. In reviewing these areas it becomes apparent that the majority exist in the catalytic reactor design. This, obviously, is a result of the moisture removal subsystem being a more highly developed technology. The following is a list of these areas, not necessarily in the order of their importance:

a. Reactor Temperature Control

Reaction rate is critically dependent upon the temperature entering the catalyst bed. Reactor outlet temperature depends on both its inlet temperature and reaction rate. This means that small changes in reactor inlet temperatures will result in sizeable changes to reactor outlet temperatures and, consequently, heat exchanger inlet temperatures. The system design uses ram air modulation to control reaction rates and heat exchanger inlet temperatures. Because of this amplification of heat exchanger inlet temperature variations by reactor characteristics, this ram control may be inadequate to prevent unacceptable temperature transients.

b. Reactor Installation Hazards

There is reasonable confidence that reactor geometries can be evolved which will not result in hazardous conditions existing within the system itself. Because of catalyst characteristics, it has been desirable to design the system using fuel-rich mixtures throughout the catalyst beds. The concern in this case relates to the potential leakage of this fuel-rich mixture to ambient which can result in combustible mixtures close to the reactor beds. This leaking gas can, in certain areas, not only be fuel-rich but also of very high temperatures where auto ignition could occur. The reactor design configuration has been selected with the best possible means of sealing the leakage controls. Nevertheless, it may be necessary to make installation arrangements which will purge this region of combustible products.

c. Reactor Feed Mixture Control

Reaction rates are not only a function of inlet temperatures but also of fuel air ratios. The present control system uses two position fuel flow controls, either high or low. This results in some variation in fuel air ratios and these variations can aggravate the problem of reactor temperature control. If operation of this system shows that adequate temperature control cannot be maintained through ram flow modulation, it may be necessary to incorporate a more sophisticated fuel control system.

d. Reaction Temperature Control in Transients

Again, reactor temperature control is accomplished by ram air. But, when flow is decreased or increased as a result of switching from low-mode to high-mode, this temperature fluctuation can be amplified substantially. In the present design it is assumed that these transients can be accommodated by proper timing between the change in fuel flow rate and bleed air flow rate.

The ultimate timing and sequence of these controls will have to be established as a result of the test program.

e. Flow Distribution in Reactor Bed

Reactor temperatures and catalyst breakdowns will depend very heavily on the ability to get uniform mixtures across the face of the catalyst bed. This need for uniformity of mixture is most apparent when it is noted that higher reaction rates in any locality raise local temperatures which, in turn, increase reaction rates. The system design has arrived at the first configuration for introducing bleed air into the reactor, but the final distribution system will have to be established in the test program. Variations to this distributor can be readily accommodated in the current design configuration.

f. Start-Up Timing

In the start-up mode, the system is filled with oxygen-rich mixture relative to normal steady state operation. It is therefore necessary in the start-up mode to add fuel at a relatively slow rate to prevent

overheating of any reactor elements. A means for accomplishing this has been incorporated in the design and a sequence of operation has been established but the final fuel flow rate and timing again must be established in the experimental program.

g. Heat Exchanger Life at High Temperatures

The heat exchangers in the reactor area are continually exposed to temperatures which are higher than current technology aircraft heat exchangers. There is reasonable confidence that at these temperature levels, the heat exchanger design will perform adequately. If reactor bed temperature controls cannot maintain these temperatures at all times, a jeopardy is placed on the heat exchangers durability.

The ability of the heat exchangers to meet increased temperature requirements will depend upon the temperature distribution as well as the magnitude and duration of these transients. How much the heat exchanger designs can be modified to accommodate these transients is uncertain until these variations are determined.

h. Effect of Acidity on Component Life

Test results from the catalyst test program indicate that the effluent mixtures contain a relatively acid mixture. In the laboratory type tests though, it is difficult to be certain how much dilution of these acids will occur in the final system. This level of acidity obviously will have an effect on the degree of corrosion on all the downstream components. A measurement of this acidity will be essential in the experimental program to determine its effect on system life.

9.0 CONCLUSIONS

9.1 General

The combustion type fuel tank inerting system is capable of maintaining noncombustibility in an aircraft fuel tank system over an entire mission profile. The combustion type is inherently rate limited. System size and weight are substantially proportional to the maximum inert gas flow rate specified, and the maximum rate occurs during descent. The more rapid the descent rate under which inerting is required, the greater the necessary inert gas flow rate. Necessary flow rate is also proportional to the total fuel tank ullage volume at the time of the maximum rate of descent. A fast descent with nearly empty tanks would govern the design.

In contrast, the liquid nitrogen type fuel tank inerting system is not rate limited. It can easily supply inert gas to the highest rates because it need only pump liquid through small, insulated lines and spray it over large expanses of fuel for evaporation. The liquid nitrogen system, instead, is total mass limited. It must carry all the inertant from the ground for the entire mission or series of missions if need be. It is limited in the total number of climb and descent cycles it can perform before its stored mass must be replenished. The combustion type inerting system has no limit on stored mass as it gets its supply from the atmosphere except for a small quantity of fuel from the tanks it inerts.

Combustion of fuel produces products that vary with the chemical composition of the fuel. Sulfur in the fuel becomes sulfur dioxide gas which may be readily oxidized to sulfur trioxide. These two gases have a strong affinity to water and tend to be collected with the moisture removed from the inert gas. They are highly corrosive, and dissolved in the water become approximately 0.01 normal sulfurous or sulfuric acid. The inerting system components that encounter moisture must therefore be made corrosion resistant. Any small amount of moisture that is not separated and remains entrained in the inert gas supplied to the fuel tanks can be considered to be acidic. It is important to regard this as a problem for further study. Actual quantities must be measured and the average and maximum rates of corrosive attack on fuel tanks must be quantitatively determined. Means of absorbing, neutralizing or resisting the small quantities of acid produced must be carefully evaluated.

There is a wide range of flow rates demanded of an inerting system over the mission profile. During cruise, flow rate is at a minimum, determined by the volume rate of fuel consumption. During climb, this rate is arbitrarily determined, to agitate the fuel and purge it of dissolved

oxygen. Flow rate is based on experiments with agitation, on climb rate, and on the presumed initial fuel condition. The flow rate during descent may be 100 or 200 times greater than that required for cruise. Continuous operation of the inerting system at substantially greater than required rates can add weight to the mission penalty. It is desirable to design the system for the least reasonable flow rate in descent and to avoid unnecessary discharge of inert gas during extended periods such as in cruise. Any scheme that would permit redefinition of the fuel tank hazard so as to reduce the inert gas flow requirements would result in advantageous weight reduction. One such means would involve permitting the fuel tank to breathe air during rapid or emergency descent, to be replaced at once by the action of the inerting system. The exact hazard in such an event would be dependent on the design details of the tank and venting system and would require experimental investigation. Operational probabilities of ignition should also be evaluated.

An extension of this philosophy to the design point of the system would result in a substantial reduction of system size. Because the designed inerting system provides an 0_2 concentration well below the allowable maximum, it is possible to supplement the inert products with raw engine bleed and still maintain an inert tank. It has been determined by analysis that the design flow rate, and similarly the system weight, could be reduced to 40% of the present size and maintain, at the completion of the maximum normal descent, a tank 0_2 fuel concentration below 9%. The significance of this weight saving justifies a reexamination of emergency descent requirements since that is the only consideration that prevents this reduction. Based on the requirements of this study, which are very severe, the reduced system would result in a tank 0_2 concentration above 9%. It would appear that some relaxation of these emergency descent requirements can be justified, thereby allowing a reduction in the B-1 system size. If these requirements cannot be relaxed, then an alternate means for providing emergency flow should be sought.

9.2 Alternate Systems Comparison

Table XII compares weights of several possible inerting systems. It must be reemphasized that these are weights of systems designed for the specified mission. As discussed in other sections of this report, ultimate mission requirements will be far less severe, thereby yielding corresponding reductions in system weights. In addition, it is anticipated that further research will provide the basis for reductions in both system complexity and weight not possible in the liquid nitrogen system.

Table XII

INERTING SYSTEM COMPARISON

Weights (lb)	LN_2 Inerting System	Combustion Inerting System			
		Catalytic Reactor		Burner	
		Continuous	Intermittent	Continuous	Intermittent
Inert Gas	797	(6170)	(797)	[illegible]	[illegible]
Fuel Burned	0	692	[illegible]	692	[illegible]
Bleed Penalty	0	247	32	[illegible]	[illegible]
Ram Penalty	0	125	[illegible]	[illegible]	[illegible]
50% Reserve	398	0	0	[illegible]	[illegible]
System	632	916	916	636	[illegible]
Installation	190	275	275	216	216
Total	2017	2255	1298	1966	1009

Flight Mode/Duration (min) = Climb/7, Cruise/[illegible], Descent 10
Fuel Tank Volume = 40,000 gal.

A liquid nitrogen system is shown as a standard of reference. Combustion inerting can be performed with a catalytic reactor or with a burner. Either combustion system can be operated full time but with flow turned down to a low rate during cruise and climb. Also, either can be operated intermittently to conserve expendables. These five cases are tabulated and weight equivalents are given for expendables.

The weight of inert gas required over the mission profile is stored weight for the nitrogen system. The others come from the atmosphere, but there is a penalty in the form of engine fuel consumed to compress the bleed air. There is another penalty in the form of engine fuel consumed to overcome the drag on the ram air. These penalties are tabulated. The nitrogen system has been assigned a 50% reserve capacity to summarily account for boil-off, unusable liquid, and for flight contingencies involving departures from the mission profile. An additional climb and descent could easily consume the reserve nitrogen.

Fixed system weights have been tabulated. Each combustion system is sized for its maximum rate required. This turns out to be the maximum normal rate of descent for sizing the moisture removal subsystem, and the emergency descent rate for sizing the combustion subsystem. The burner type is seen to be substantially lighter than the catalytic reactor combustion subsystem. This is the result of the light sheet metal design of the burner as opposed to the greater weight of catalyst bed and to corresponding heat exchanger design advantages.

Installation weights include supports, ducting and distribution nozzles. The combustion systems are heavier than the nitrogen system in this area because they have engine bleed air ducting and primary heat exchanger and firewall weights in addition to ram air ducting and larger diameter distribution ducting. The nitrogen system has only the smaller distribution ducting, supports and distribution spray nozzles.

Total weights show that the intermittent operation of the combustion system can save up to 1000 lb, a large portion of which is the weight of fuel burned in the inerting system. The burner type combustion system is lighter than the catalytic reactor type by about 230 pounds, primarily because the burner and heat exchanger is that much lighter than the catalyst beds and heat exchangers. The intermittently operating burner system is one-half the weight of the nitorgen system, while the intermittently operating catalyst system is 60% as heavy. Both steady operation combustion systems are essentially the same weights as the nitrogen system, with the catalytic system only slightly heavier.

It is to be concluded from this weight summary that intermittent operation is one method by which a significant weight advantage can be made by the combustion type inerting system.

The greatest part of the weight penalty difference between continuous and intermittent operation, where continuous is based on 10% full capacity minimum flow, results from the extremely long cruise duration of 900 minutes (15 hours).

It should be reiterated that this weight comparison is based on a single mission. When multiple missions are considered without replenishment of expendables, the weights of the nitrogen system will increase proportionately - putting that system at a sizable disadvantage. For example, if the system has to be designed to complete two missions without replenishment as is reasonable because of logistics with the bare-base concept, the total weight of the nitrogen system would increase from 2017 pounds to 3360 pounds. There would be no effect on the combustion type system.

9.3 Corrosive Gases

Products of combustion include sulfur dioxide and a small amount of nitrogen oxides. In combination with moisture condensed from the combustion products, these gases produce corrosive acids which can attack the system components and the fuel tanks. It is necessary to resolve the problem of corrosion in order to justify acceptance of a combustion type inerting system. The inital approach is to rely upon the high solubility of the acid gases to produce separation from the inert gas by solution in the condensed moisture which is then removed from the system.

Experience with gas turbine corrosion from combustion products indicates that the primary problem comes from sulfur dioxide. Nitrogen oxides have been of negligible quantity in comparison. Test results from the American Cyanamid program included a sampling of condensate from the test reactor output. Those samples were strongly acid with pH values of about 2. It is not known what fraction of the gaseous sulfur dioxide was dissolved. Corrosive gases are of concern primarily to the aircraft structure, the fuel tank itself. The inerting system can be designed to be corrosion resistant to the extent necessary, but the aircraft structure should not require modification nor be endangered.

Further work is necessary to resolve the corrosion problem. It is desirable first to determine the quantity of SO_2 gas and the quantity and concentration of dissolved SO_2 entering the fuel tank. An effort should be made to determine the solubility of SO_2 gas and of its aqueous solution in the fuel. With these data, a determination can be made using metallurgical references that will yield the actual corrosion rate on the aircraft fuel tank structural materials. Finally, the predicted corrosion rate must be compared with the allowable rate in order to conclusively decide on the acceptability of combustion products with moisture removal as a fuel tank inerting gas. Some effort should be applied to verify the probable unacceptability of a solid adsorbent bed for the removal of SO_2 from the flowing gas. Such a bed is likely to be very large and heavy because of the large volume flow rate of inert gas supplied to the tanks.

10.0 RECOMMENDATIONS

This study has analytically established the feasibility of a catalytic combustor type fuel tank inerting system. On the basis of this work it is recommended that the program be continued through the next experimental program phase. The experimental program should generally be directed at the development areas listed in Section 8. It should cover, as a minimum, the following specific topics:

a. Fuel injection, mixing and distribution
b. Bleed air injection and distribution
c. Reactor bed temperature control
d. System start-up and shut-down
e. Corrosive characteristics of the inerted gas

APPENDIX I

Design Calculations: Segmented Reactor for Fuel Tank Inerting

The following calculation methods apply to the case in which all of the fuel is added to the recycle stream, and the bleed air stream is divided among the reactor segments. Figure 2 shows the flow leaving the final reactor segment. The nomenclature used in the calculations is presented in Table A-I.

I. Overall Relationships

A. Stoichiometry

The following stoichiometry is assumed:

Basis: 100 lb-moles air, 100% conversion

$$1.4\, C_{10}H_{20} + 21\, O_2 + 79\, N_2 \qquad 14\, CO_2 + 14\, H_2O + 79\, N_2$$

At an overall conversion of X_T:

$$1.4\, X_T\, C_{10}H_{20} + 21\, O_2 + 79\, N_2 \qquad 14\, X_T\, CO_2 + 14\, X_T\, H_2O$$

$$+ 21\,(1-X_T)\, O_2 + 79\, N_2$$

Stoichiometric fuel/air ratio (weight basis)

$$= \frac{(1.4)\,(140)}{(21)(32) + 79\,(28)} = 0.0679$$

B. Material Balance

Air and Fuel Flow Rates. From Figure 2 and Table A-1,

Fuel + Air = 1-R

Fuel/Air ratio = B

$$\text{Fuel Rate} = B\,\frac{(1-R)}{(1+B)},\ \text{lbs/hr}$$

$$\text{Air Rate} = \frac{(1-R)}{(1+B)},\ \text{lbs/hr}$$

Dry Ballast Gas Rate. From stoichiometry, the ratio of dry ballast gas out to air in is

$$= \frac{(14)\,(44)\,(X_T) + (21)(32)(1-X_T) + (79)(28)}{(21)(32) + (79)\,(28)} = (1-0.0194X_T).$$

Table A-1 Nomenclature: Segmented Reactor

n		number of reactor segments
R		recycle ratio
X_T		overall fractional conversion of oxygen
X_i		fractional conversion of oxygen in ith reactor segment
A_i		Air input to ith reactor segment, lbs/hr
a_i	,	air flow coefficient, $= A_i/\Sigma A_i$; $\Sigma a_i = 1.0$
F_i	=	Total gas flow through ith reactor segment, lbs/hr
M_i		oxygen converted in ith reactor segment, lbs/hr
m_i	,	conversion coefficient, $= M_i/\Sigma M_i$; $\Sigma m_i = 1.0$
y_i^1		oxygen concentration entering ith reactor segment, weight fraction
y_i^o	=	oxygen concentration leaving ith reactor segment, weight fraction
B	=	overall fuel/air ratio, lbs/lb
K	=	reaction rate constant, hr^{-1}
SV	=	space velocity, hr^{-1} (volume gas flow per hour per volume of catalyst; gas volume measured at 14.7 psia, 72.5°F)
BG	=	Dry ballast gas demand, lbs/min (actual scale)
W_2	=	weight of catalyst in ith reactor segment, lbs. (actual scale)
Duct size	=	size of square duct, ft. (actual scale)
ΔT_i design	=	temperature rise in ith reactor segment at design flow, °F
ΔT_i 100	=	temperature rise in ith reactor segment at 100% conversion in that segment °F
ΔP_i	=	pressure drop in ith reactor segment, psi.
ℓ_i	=	thickness of ith reactor segment, inches

$\therefore$ Dry Ballast Gas Rate

$$= \frac{(1-R)}{(1+B)} \; (1-0.0194X_T), \text{ lbs/hr}$$

Exit Oxygen Concentrations

Oxygen out $= (0.233)(1-X_T)(1-R)/(1+B)$, lbs/hr.
Weight fraction O_2 in wet ballast gas leaving n^{th} reactor

$$(0.233)(1-X_T)\frac{(1-R)}{(1+B)}/(1-R) = (0.233)(1-X_T)/(1+B)$$

Weight fraction O_2 in dry ballast gas

$$(0.233)(1-X_T)\frac{(1-R)}{(1+B)} / \frac{(1-R)}{(1+B)}(1-0.0194X_T)$$

$$(0.233)(1-X_T) / (1-0.0194X_T)$$

Volume fraction O_2 in dry ballast gas

$$\frac{21(1-X_T)}{79+14X_T+21(1-X_T)} = (0.21)(1-X_T) / (1-0.07X_T)$$

Average Molecular Weight of Dry Ballast Gas

$$= 32\frac{(\text{Vol\% } O_2)}{(\text{Wt\% } O_2)} = 28.84\ (1-0.0194X_T) / (1-0.07X_T)$$

II. Calculations for Individual Reactor Segments

A. General Case:

Specific values are assigned to the following variables: n, R, X_T, all air flow coefficients (a_i), all conversion coefficients (m_i), B, K, P_{ave}, ℓ_{min}, and BG

1. Calculation of Conversions and Concentrations

a) Calculate all A_i

$$A_i = a_i \quad \Sigma A_i = a_i\ (1-R) / (1+B)$$

b) Calculate all F_i

$$F_i = R + B\frac{(1-R)}{(1+B)} + A_1 + A_2 + \ldots.\ A_i$$

c) Calculate all M_i

$$\Sigma M_i = (0.233)(X_T)(1-R) / (1+B)$$

$M_i \quad m_i \quad \Sigma M_i \quad m_i (0.233)(X_T)(1-R) \quad (1+B)$

d) Then:

$$y_n^0 = (0.233)(1-X_T) / (1+B)$$
$$y_1^1 = (y_n^0 R + 0.233 A_1) / F_1$$
$$y_1^0 = y_1^1 - \frac{M_1}{F_1}$$
$$y_2^1 = (y_1^0 F_1 + 0.233 A_2) / F_2$$
$$y_2^0 = y_2^1 - \frac{M_2}{F_2}$$

etc. ----

$$\text{to } y_n^1 = (y_{n-1}^0 F_{n-1} + 0.233 A_n) / F_n$$
$$\text{and } y_n^0 = y_n^1 - \frac{M_n}{F_n}$$

e) Calculate fractional conversions in each segment

$$X_i = \frac{M_i}{y_i^1 \; F_i}$$

2. Calculation of temperature rise in each bed.

Heat release = 18,500 BTU/lb fuel consumed
Average heat capacity of gas = 0.265 BTU/(lb)(°F)

$$\therefore (18,500) \frac{(0.0679)}{(0.233)} (M_i) = (0.265)(F_i)\,\Delta T_i \text{ design}$$

and ΔT_i design = 20,300 M_i/F_i

At low flow, X_i approaches 1.0 and M_i approaches 0.233 A_i

$$\therefore \Delta T_{i\ 100} = (20,300)\ (0.233\ A_i)/F_i = 4730\ A_i/F_i$$

3. Calculation of space velocities in each bed.

$$SV_i = K \Big/ \ln \frac{1}{(1-X_i)}$$

4. Calculation of weights for each bed.

$$SV_i = \frac{F_i\ (359)\ (532.5)}{(MW_{ave})\ (492)} \Bigg/ \frac{W_i}{\rho cat} \qquad \left\{ \begin{array}{l} \rho cat = 40.6 \text{ lbs/ft}^3 \\ MW_{ave} \cong 29.5 \end{array} \right.$$

$\therefore\ W_i = (6.90535)(F_i)/(SV_i \times 10^{-5})$,

for basis of 1 lb/hr gas leaving n^{th} segment

5. Scale-up to actual case.

If the ballast gas demand for an actual case is BG lbs/min, then the scale-up factor (S) from the basis of 1 lb/hr gas leaving the final reactor segment is:

$$S = (BG)(60)\left[\frac{(1+B)}{(1-R)(1-0.0194X_T)}\right]$$

and $W_i = (W_i)\ (S)$

6. Calculation of Duct Size.

Bed Volume $= W_i/\rho cat = W_i/40.6$, cu. ft.

Bed Area $= \frac{W_i\ (12)}{(40.6)\ (\ell_i)} = 0.295\ W_i/\ell_i$, ft^2

Duct Size $= 0.543\ (W_i/\ \ell_i)^{1/2}$ = side of square duct, ft.

7. Calculation of pressure drop through each bed.*

For each bed:

$$\Delta P = \frac{\frac{2.36}{144}\ (\mu^{0.15})\ (\ell)\ (\rho^{0.85})\ (V_0^{1.85})}{D_P^{1.15}} \cdot A_f$$

where $\mu = 0.0000268$ lbs/ft-sec
$D_p = 0.00625$ ft

a_f = wall effect factor, assumed = 1.0
ℓ = bed thickness, ft.

The above equation is for turbulent flow, which will generally apply at the flow rates encountered here: $\left[\frac{D_p V_o}{\mu} > 40\right]$

*References: Technical Report AFAPL-TR-69-68, Generation of Inerting Gases for Aircraft Fuel Tanks by Catalytic Combustion Techniques", American Cyanamid Company, August 1969.

Chemical Engineers Handbook, John H. Perry, Ed., 3rd Edition, P. 393, McGraw Hill, New York (1950)

$$\rho = \frac{(29)(492)(P_{ave})}{(359)(T_{ave})(14.7)}, \quad P \text{ and } T \text{ at reactor conditions}$$

$$V_0 = \frac{(SV)(\ell)(14.7)(T_{ave})}{(3600)(12)(P_{ave})(532.5)}, \quad \text{where } \ell \text{ is in inches.}$$

Combining,

$$\Delta P_i = 0.0014 \left(\frac{T_{ave}}{P_{ave}}\right)(SV_i \times 10^{-3})^{1.85} (\ell_i)^{2.85}$$

	Units
T_{ave}	$^{\circ}R$
P_{ave}	Psia
SV	hr^{-1} (calculated for gas volume at 14.7 psia, 72.5°F)
ℓ	inches

Note: In calculating pressure drops, if ℓ_{min} is specified for smallest reactor segment, the thickness of the other beds is proportional to their weights, assuming constant cross-section in all segments.

8. Bypass Factor

Some of the ballast gas requirement may be allowed to bypass reactor to give a final oxygen concentration in the dry ballast gas, y_f, which is higher than that leaving the reactor but still meets inerting requirements. For this case a bypass factor, z, representing the fraction of the total ballast gas requirement passing through the reactor may be calculated:

$$z = \frac{(0.233-y_f)(1-0.0194X_T)}{0.229X_T}$$

A very close approximation to z is given by the simpler expression:

$$z = \frac{(0.233-y_f)}{0.233X_T}$$

The weights calculated without bypass can then be multiplied by z and the duct size by $(z)^{1/2}$. Pressure drops, temperature rise, and oxygen concentrations throughout the reactor system remain the same.

B. Special Cases

1. Special case in which the reactor segments are sized so that at design flow the heat release in each segment is proportional to the flow through that segment, and ΔT_{Design} is equal for all segments. For this case it can be shown that:

$$\frac{M_i}{F_i} = \text{constant} = \frac{\Sigma M_i}{\Sigma F_i}$$

$$\therefore M_i = (\Sigma M_i)(F_i)/\Sigma F_i$$

ΣM_i and F_i are calculated as in Section A1.

$$\Sigma F_i = F_1 + F_2 + \ldots + F_n$$

$$= nR + \frac{(1-R)}{(1+B)}\left[n(B+a_1) + (n-1)a_2 + (n-2)a_3 + \ldots a_n\right]$$

$\therefore$ all M_i can be calculated, and all other quantities as in the general case.

Note that ΔT_{Design} may be specified rather than R. In this case, R can be calculated by trial and error from:

$$\Delta T_{Design} = (20,300)\ \Sigma M_i / \Sigma F_i$$

2. Special case in which air flow is split so that the air fed to each reactor segment is proportional to the total flow through that segment. For this case, the temperature rise in each bed at low flow would approach $T_{i\ 100}$ as a limit as the conversion in that bed approached 100%.

For this case it can be shown that:

$$\frac{A_i}{F_i} = \text{constant} = 1 - \left(\frac{R+B}{1+B}\right)^{\frac{1}{n}}$$

$$F_i = \left(\frac{R+B}{1+B}\right)^{\frac{n-i}{n}}$$

$$\text{and } A_i = \left(\frac{R+B}{1+B}\right)^{\frac{n-i}{n}}\left[1 - \left(\frac{R+B}{1+B}\right)^{\frac{1}{n}}\right]$$

At 100% conversion in each bed,

$$M_i = 0.233\ A_i$$

$$M_i / F_i = 0.233\ A_i / F_i$$

and $$\Delta T_{i\ 100} = 26,300\ \frac{M_i}{F_i} - 4730 \left[1 - \left(\frac{R+B}{1+B} \right)^{\frac{1}{n}} \right]$$

Note that either R or $\Delta T_{i\ 100}$ may be specified in this case.

3. <u>Special case</u> in which the conditions for both special cases 1 and 2 apply, i.e.,

$\frac{M_i}{F_i}$ = constant, ΔT_{Design} equal for all beds

and $\frac{A_i}{F_i}$ = constant, ΔT_{100} equal for all beds

For this case, only one of the three quantities R, ΔT_{Design} and ΔT_{100} need be specified to determine the others, (assuming n, X_T, and B are also specified).

4. <u>Special case</u> in which bed weights are specified. This case is useful if it is desired, for example, to design a system where all segments are of equal weight and thickness. The relationships given under the general case apply, but a trial and error approach is required, once the fractional conversions in each bed have been calculated from the bed weights.

Appendix II
Reactor Design Calculations: Computer Output Data

In the following tables, the values given for bed weight and duct size are for the scale indicated by the specified ballast gas demand. Air flow, total flow, and oxygen converted in each bed are scaled to an output of 1 lb/hr of wet gas leaving the final reactor segment. The latter quantities may be converted to the same basis as the ballast gas demand by multiplying by the scale-up factor given in each table.

RUN NO. 1 FTI SEGMENTED REACTOR CASE 3 DATE 8/ 4/70

SPECIFIED VARIABLES

NUMBER OF BEDS= 3 FUEL AIR RATIO= .0746 BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN. AVERAGE PRESSURE= 50.0PSIA REACTION RATE CONSTANT= 194000.0/HR
RECYCLE RATE= .6500 OVERALL CONVERSION= .90 AIR FLOW COEFFICIENTS

CALCULATED VARIABLES

TEMP. RISE AT DESIGN COND.= 521.3 DEG F
DUCT SIZE= 2.65 FT. SCALE UP FACTOR= 15000.7

	BED 1	BED 2	BED 3	TOTAL
AIR FLOW(LBS./HR)	.1086	.1086	.1086	.3257
AIR FLOW COEFFICIENT	.3333	.3333	.3333	.9999
TOTAL FLOW(LBS./HR)	.7829	.8214	1.0000	2.6742
OXYGEN CONVERTED(LBS./HR)	.0201	.0229	.0257	.0687
CONVERSION COEFFICIENT	.2927	.3333	.3739	1.0000
OXYGEN CONCENTRATION IN	.0494	.0492	.0463	
OXYGEN CONCENTRATION OUT	.0237	.0235	.0206	
FRACTIONAL CONVERSION	.5197	.5218	.5550	
TEMP. RISE AT DESIGN COND.	521.34	521.34	521.34	
TEMP. RISE AT 100 PCT CONV.	655.90	576.02	513.49	
SPACE VELOCITY/10**5 (1/HR)	2.6451	2.6295	2.3960	
BED WEIGHT (LBS.)	23.75	27.21	33.49	84.45
PRESSURE DROP (PSI)	.2601	.3788	.5769	1.2158

RUN NO. 2 FTI SEGMENTED REACTOR CASE 3 DATE 8/ 4/70

SPECIFIED VARIABLES

NUMBER OF BEDS= 3 FUEL AIR RATIO= .0746 BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN. AVERAGE PRESSURE= 50.0PSIA REACTION RATE CONSTANT= 194000.0/HR
RECYCLE RATE= .6500 OVERALL CONVERSION= .86 AIR FLOW COEFFICIENTS

CALCULATED VARIABLES

TEMP. RISE AT DESIGN COND.= 493.7 DEG F
DUCT SIZE= 2.28 FT. SCALE UP FACTOR= 14986.5

	BED 1	BED 2	BED 3	TOTAL
AIR FLOW(LBS./HR)	.1086	.1086	.1086	.3257
AIR FLOW COEFFICIENT	.3333	.3333	.3333	.9999
TOTAL FLOW(LBS./HR)	.7829	.8914	1.0000	2.6742
OXYGEN CONVERTED(LBS./HR)	.0190	.0217	.0243	.0650
CONVERSION COEFFICIENT	.2927	.3333	.3739	1.0000
OXYGEN CONCENTRATION IN	.0581	.0580	.0553	
OXYGEN CONCENTRATION OUT	.0337	.0337	.0310	
FRACTIONAL CONVERSION	.4189	.4193	.4396	
TEMP. RISE AT DESIGN COND.	493.69	493.69	493.69	
TEMP. RISE AT 100 PCT CONV.	655.90	576.02	513.49	
SPACE VELOCITY/10**5 (1/HR)	3.5736	3.5693	3.3497	
BED WEIGHT (LBS.)	17.56	20.02	23.93	61.52
PRESSURE DROP (PSI)	.4579	.6638	.9814	2.1032

RUN NO. 3 FTI SEGMENTED REACTOR CASE 3 DATE 8/ 4/70

SPECIFIED VARIABLES

NUMBER OF BEDS= 3	FUEL AIR RATIO= .0746	BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN.	AVERAGE PRESSURE= 50.0PSIA	REACTION RATE CONSTANT= 194000.0/HR
RECYCLE RATE= .6500	OVERALL CONVERSION= .81	AIR FLOW COEFFICIENTS

CALCULATED VARIABLES

TEMP. RISE AT DESIGN COND.= 466.6 DEG F
DUCT SIZE= 2.01 FT. SCALE UP FACTOR= 14972.7

	BED 1	BED 2	BED 3	TOTAL
AIR FLOW(LBS./HR)	.1086	.1086	.1086	.3257
AIR FLOW COEFFICIENT	.3333	.3333	.3333	.9999
TOTAL FLOW(LBS./HR)	.7829	.8914	1.0000	2.6742
OXYGEN CONVERTED(LBS./HR)	.0180	.0205	.0230	.0615
CONVERSION COEFFICIENT	.2927	.3333	.3739	1.0000
OXYGEN CONCENTRATION IN	.0665	.0664	.0642	
OXYGEN CONCENTRATION OUT	.0435	.0436	.0412	
FRACTIONAL CONVERSION	.3456	.3451	.3582	
TEMP. RISE AT DESIGN COND.	466.62	466.62	466.62	
TEMP. RISE AT 100 PCT CONV.	655.90	576.02	513.49	
SPACE VELOCITY/10**5 (1/HR)	4.5755	4.5830	4.3750	
BED WEIGHT (LBS.)	13.71	15.58	18.31	47.59
PRESSURE DROP (PSI)	.7297	1.0547	1.5330	3.3174

RUN NO. 4 FTI SEGMENTED REACTOR CASE 3 DATE 8/ 4/70

SPECIFIED VARIABLES

NUMBER OF BEDS= 3 FUEL AIR RATIO= .0746 BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN. AVERAGE PRESSURE= 50.0PSIA REACTION RATE CONSTANT= 194000.0/HR
RECYCLE RATE= .6500 OVERALL CONVERSION= .76 AIR FLOW COEFFICIENTS

CALCULATED VARIABLES

TEMP. RISE AT DESIGN COND.= 439.0 DEG F
DUCT SIZE= 1.30 FT. SCALE UP FACTOR= 14958.5

	BED 1	BED 2	BED 3	TOTAL
AIR FLOW(LBS./HR)	.1086	.1086	.1086	.3257
AIR FLOW COEFFICIENT	.3333	.3333	.3333	.9999
TOTAL FLOW(LBS./HR)	.7829	.8914	1.0000	2.6742
OXYGEN CONVERTED(LBS./HR)	.0169	.0193	.0216	.0578
CONVERSION COEFFICIENT	.2927	.3333	.3739	1.0000
OXYGEN CONCENTRATION IN	.0752	.0754	.0732	
OXYGEN CONCENTRATION OUT	.0535	.0538	.0516	
FRACTIONAL CONVERSION	.2877	.2868	.2953	
TEMP. RISE AT DESIGN COND.	438.96	438.96	438.96	
TEMP. RISE AT 100 PCT CONV.	655.90	576.02	513.49	
SPACE VELOCITY/10**5 (1/HR)	5.7180	5.7390	5.5427	
BED WEIGHT (LBS.)	10.96	12.43	14.44	37.83
PRESSURE DROP (PSI)	1.1118	1.6039	2.3042	5.0199

RUN NO. 5 FTI SEGMENTED REACTOR CASE 3 DATE 8/ 5/70

SPECIFIED VARIABLES

NUMBER OF BEDS= 2 FUEL AIR RATIO= .0746 BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN. AVERAGE PRESSURE= 50.0PSIA REACTION RATE CONSTANT= 194000.0/HR
RECYCLE RATE= .7500 OVERALL CONVERSION= .81 AIR FLOW COEFFICIENTS

CALCULATED VARIABLES

TEMP. RISE AT DESIGN COND.= 473.2 DEG F
DUCT SIZE= 2.57 FT. SCALE UP FACTOR= 20961.7

	BED 1	BED 2	TOTAL
AIR FLOW(LBS./HR)	.1163	.1163	.2326
AIR FLOW COEFFICIENT	.5000	.5000	1.0000
TOTAL FLOW(LBS./HR)	.8837	1.0000	1.8837
OXYGEN CONVERTED(LBS./HR)	.0206	.0233	.0439
CONVERSION COEFFICIENT	.4691	.5309	1.0000
OXYGEN CONCENTRATION IN	.0656	.0645	
OXYGEN CONCENTRATION OUT	.0423	.0412	
FRACTIONAL CONVERSION	.3551	.3613	
TEMP. RISE AT DESIGN COND.	473.18	473.18	
TEMP. RISE AT 100 PCT CONV.	922.63	550.20	
SPACE VELOCITY/10**5 (1/HR)	4.4221	4.3265	
BED WEIGHT (LBS.)	22.[illegible]	25.92	48.33
PRESSURE DROP (PSI)	.6836	.9939	1.6775

RUN NO. 5A FTI SEGMENTED REACTOR CASE 3 DATE 8/ 4/70

SPECIFIED VARIABLES

NUMBER OF BEDS= 3 FUEL AIR RATIO= .0746 BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN. AVERAGE PRESSURE= 50.0PSIA REACTION RATE CONSTANT= 194000.0/HR
RECYCLE RATE= .7500 OVERALL CONVERSION= .81 AIR FLOW COEFFICIENTS

CALCULATED VARIABLES

TEMP. RISE AT DESIGN COND.= 322.1 DEG F
DUCT SIZE= 2.15 FT. SCALE UP FACTOR= 20961.7

	BED 1	BED 2	BED 3	TOTAL
AIR FLOW(LBS./HR)	.0775	.0775	.0775	.2326
AIR FLOW COEFFICIENT	.3333	.3333	.3333	.9999
TOTAL FLOW(LBS./HR)	.8449	.9224	1.0000	2.7673
OXYGEN CONVERTED(LBS./HR)	.0134	.0146	.0159	.0439
CONVERSION COEFFICIENT	.3053	.3333	.3614	1.0000
OXYGEN CONCENTRATION IN	.0580	.0581	.0571	
OXYGEN CONCENTRATION OUT	.0421	.0423	.0412	
FRACTIONAL CONVERSION	.2738	.2729	.2781	
TEMP. RISE AT DESIGN COND.	322.09	322.09	322.09	
TEMP. RISE AT 100 PCT CONV.	434.10	397.61	366.78	
SPACE VELOCITY/10**5 (1/HR)	6.0644	6.0368	5.9541	
BED WEIGHT (LBS.)	15.62	17.00	18.83	51.45
PRESSURE DROP (PSI)	1.2855	1.6450	2.1165	5.0472

RUN NO. 6 FTI SEGMENTED REACTOR CASE 3 DATE 8/ 5/70

SPECIFIED VARIABLES

NUMBER OF BEDS= 4 FUEL AIR RATIO= .0746 BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN. AVERAGE PRESSURE= 50.0PSIA REACTION RATE CONSTANT= 19.000.0/HR
RECYCLE RATE= .5580 OVERALL CONVERSION= .81 AIR FLOW COEFFICIENTS

CALCULATED VARIABLES

TEMP. RISE AT DESIGN COND.= 465.8 DEG F
DUCT SIZE= 1.66 FT. SCALE UP FACTOR= 11856.2

	BED 1	BED 2	BED 3	BED 4	TOTAL
AIR FLOW(LBS./HR)	.1028	.1028	.1028	.1028	.4113
AIR FLOW COEFFICIENT	.2500	.2500	.2500	.2500	1.0000
TOTAL FLOW(LBS./HR)	.6915	.7942	.8972	1.0000	3.3830
OXYGEN CONVERTED(LBS./HR)	.0159	.0182	.0206	.0229	.0776
CONVERSION COEFFICIENT	.2044	.2348	.2652	.2956	1.0000
OXYGEN CONCENTRATION IN	.0679	.0693	.0677	.0641	
OXYGEN CONCENTRATION OUT	.0449	.0463	.0448	.0412	
FRACTIONAL CONVERSION	.3380	.3312	.3388	.3577	
TEMP. RISE AT DESIGN COND.	465.81	465.81	465.81	465.81	
TEMP. RISE AT 100 PCT CONV.	703.36	612.31	542.13	486.38	
SPACE VELOCITY/10**5 (1/HR)	4.7033	4.8231	4.6901	4.3817	
BED WEIGHT (LBS.)	9.33	10.45	12.13	14.48	46.38
PRESSURE DROP (PSI)	.7680	1.1118	1.6175	2.3589	5.5562

RUN NO. 7 FTI SEGMENTED REACTOR CASE 3 DATE 8/ 4/70

SPECIFIED VARIABLES

NUMBER OF BEDS= 3 FUEL AIR RATIO= .0746 BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN. AVERAGE PRESSURE= 50.0PSIA REACTION RATE CONSTANT= 19+000.0/HR
RECYCLE RATE= .5500 OVERALL CONVERSION= .81 AIR FLOW COEFFICIENTS

CALCULATED VARIABLES

TEMP. RISE AT DESIGN COND.= 621.6 DEG F
DUCT SIZE= 1.87 FT. SCALE UP FACTOR= 11645.4

	BED 1	BED 2	BED 3	TOTAL
AIR FLOW(LBS./HR)	.1396	.1396	.1396	.4187
AIR FLOW COEFFICIENT	.3333	.3333	.3333	.9999
TOTAL FLOW(LBS./HR)	.7208	.8604	1.0000	2.5812
OXYGEN CONVERTED(LBS./HR)	.0221	.0263	.0306	.0790
CONVERSION COEFFICIENT	.2793	.3333	.3874	1.0000
OXYGEN CONCENTRATION IN	.0766	.0763	.0718	
OXYGEN CONCENTRATION OUT	.0459	.0457	.0412	
FRACTIONAL CONVERSION	.4000	.4014	.4264	
TEMP. RISE AT DESIGN COND.	621.57	621.57	621.57	
TEMP. RISE AT 100 PCT CONV.	915.88	767.31	660.21	
SPACE VELOCITY/10**5 (1/HR)	3.7980	3.7803	3.4903	
BED WEIGHT (LBS.)	11.82	14.18	17.85	43.85
PRESSURE DROP (PSI)	.4914	.8175	1.3591	2.6680

RUN NO. 8 FTI SEGMENTED REACTOR CASE 4 DATE 8/ 4/70

SPECIFIED VARIABLES

NUMBER OF BEDS= 3 FUEL AIR RATIO= .0746 BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN. AVERAGE PRESSURE= 50.0PSIA REACTION RATE CONSTANT= 194000.0/HR
TEMP. RISE AT 100 PERCENT CONV.= 700.0 OVERALL CONVERSION= .85 TEMP. RISE AT DESIGN CON

CALCULATED VARIABLES

RECYCLE RATE= .5900
DUCT SIZE= 2.23 FT. SCALE UP FACTOR= 12792.5

	BED 1	BED 2	BED 3	TOTAL
AIR FLOW(LBS./HR)	.1074	.1261	.1480	.3815
AIR FLOW COEFFICIENT	.2816	.3305	.3879	1.0000
TOTAL FLOW(LBS./HR)	.7259	.8520	1.0000	2.5779
OXYGEN CONVERTED(LBS./HR)	.0213	.0250	.0293	.0756
CONVERSION COEFFICIENT	.2816	.3305	.3879	1.0000
OXYGEN CONCENTRATION IN	.0609	.0614	.0618	
OXYGEN CONCENTRATION OUT	.0316	.0321	.0325	
FRACTIONAL CONVERSION	.4811	.4773	.4740	
TEMP. RISE AT DESIGN COND.	594.99	594.99	594.99	
TEMP. RISE AT 100 PCT CONV.	700.00	700.00	700.00	
SPACE VELOCITY/10**5 (1/HR)	2.9568	2.9907	3.0196	
BED WEIGHT (LBS.)	16.80	19.50	22.67	58.97
PRESSURE DROP (PSI)	.3120	.4869	.7611	1.5600

RUN NO. 9 FTI SEGMENTED REACTOR CASE 6 DATE 8/ 4/70

SPECIFIED VARIABLES

NUMBER OF BEDS= 3 FUEL AIR RATIO= .0746 BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN. AVERAGE PRESSURE= 50.0PSIA REACTION RATE CONSTANT= 194000.0/HR
RECYCLE RATE= .6000 AIR FLOW COEFFICIENTS BED WEIGHTS

CALCULATED VARIABLES

OVERALL CONVERSION= .84
DUCT SIZE= 2.43 FT. SCALE UP FACTOR= 13109.2

	BED 1	BED 2	BED 3	TOTAL
AIR FLOW(LBS./HR)	.1048	.1230	.1444	.3722
AIR FLOW COEFFICIENT	.2816	.3305	.3879	1.0000
TOTAL FLOW(LBS./HR)	.7326	.8556	1.0000	2.5882
OXYGEN CONVERTED(LBS./HR)	.0239	.0237	.0254	.0730
CONVERSION COEFFICIENT	.3271	.3251	.3478	1.0000
OXYGEN CONCENTRATION IN	.0615	.0582	.0597	
OXYGEN CONCENTRATION OUT	.0289	.0305	.0344	
FRACTIONAL CONVERSION	.5301	.4762	.4249	
TEMP. RISE AT DESIGN COND.	661.54	562.95	515.34	
TEMP. RISE AT 100 PCT CONV.	676.78	680.09	682.96	
SPACE VELOCITY/10**5 (1/HR)	2.5690	3.0004	3.5067	
BED WEIGHT (LBS.)	20.00	20.00	20.00	60.00
PRESSURE DROP (PSI)	.2352	.3240	.4391	.9982

RUN NO. 10   FTI SEGMENTED REACTOR CASE 4   DATE 8/ 4/70

SPECIFIED VARIABLES

NUMBER OF BEDS= 6   FUEL AIR RATIO= .0746   BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN.   AVERAGE PRESSURE= 50.0PSIA   REACTION RATE CONSTANT= 194000.0/HR
TEMP. RISE AT 100 PERCENT CONV.= 700.0   OVERALL CONVERSION= .85   TEMP. RISE AT DESIGN CON[illegible]

CALCULATED VARIABLES

RECYCLE RATE= .3365
DUCT SIZE= 1.41 FT.   SCALE UP FACTOR= 7904.0

	BED 1	BED 2	BED 3	BED 4	BED 5	BED 6	TOTAL
AIR FLOW(LBS./HR)	.0664	.0780	.0915	.1074	.1261	.1480	.61[illegible]
AIR FLOW COEFFICIENT	.1076	.1263	.1482	.1740	.2042	.2397	1.[illegible]
TOTAL FLOW(LBS./HR)	.4490	.5270	.6185	.7259	.8520	1.0000	[illegible]
OXYGEN CONVERTED(LBS./HR)	.0132	.0154	.0181	.0213	.0250	.0293	.12[illegible]
CONVERSION COEFFICIENT	.1076	.1263	.1482	.1740	.2042	.2397	1.[illegible]
OXYGEN CONCENTRATION IN	.0589	.0597	.0603	.0609	.0614	.0618	
OXYGEN CONCENTRATION OUT	.0295	.0303	.0310	.0316	.0321	.0325	
FRACTIONAL CONVERSION	.4980	.4913	.4858	.4811	.4773	.4740	
TEMP. RISE AT DESIGN COND.	594.99	594.99	594.99	594.99	594.99	594.99	
TEMP. RISE AT 100 PCT CONV.	700.00	700.00	700.00	700.00	700.00	700.00	
SPACE VELOCITY/10**5 (1/HR)	2.8151	2.8701	2.9169	2.9568	2.9907	3.0196	
BED WEIGHT (LBS.)	6.74	7.76	8.97	10.38	12.05	14.00	59.91
PRESSURE DROP (PSI)	.2849	.4411	.6850	1.0667	1.6647	2.6025	6.[illegible]

7/31/76

RUN NO. 12 FTI SEGMENTED REACTOR CASE 6 DATE 0/ 0/ 0

SPECIFIED VARIABLES

NUMBER OF BEDS= 3 FUEL AIR RATIO= .0746 BALLAST GAS DEMAND= 200.0 LBS/MIN
BED THICKNESS= 1.0 IN. AVERAGE PRESSURE= 50.0PSIA REACTION RATE CONSTANT= 194000.0/HR
RECYCLE RATE= .3750 AIR FLOW COEFFICIENTS BED WEIGHTS

CALCULATED VARIABLES

OVERALL CONVERSION= .66
DUCT SIZE= 2.43 FT. SCALE UP FACTOR= 20899.9

	BED 1	BED 2	BED 3	TOTAL
AIR FLOW(LBS./HR)	.1638	.1922	.2256	.5816
AIR FLOW COEFFICIENT	.2816	.3305	.3879	1.0000
TOTAL FLOW(LBS./HR)	.5822	.7744	1.0000	2.3566
OXYGEN CONVERTED(LBS./HR)	.0296	.0293	.0306	.0894
CONVERSION COEFFICIENT	.3305	.3274	.3421	1.0000
OXYGEN CONCENTRATION IN	.1131	.1047	.1043	
OXYGEN CONCENTRATION OUT	.0623	.0669	.0738	
FRACTIONAL CONVERSION	.4490	.3612	.2932	
TEMP. RISE AT DESIGN COND.	1030.51	767.36	621.06	
TEMP. RISE AT 100 PCT CONV.	1330.69	1174.10	1067.12	
SPACE VELOCITY/10**5 (1/HR)	3.2547	4.3294	5.5907	
BED WEIGHT (LBS.)	20.00	20.00	20.00	60.00
PRESSURE DROP (PSI)	.3185	.5954	1.0049	1.9188

8/31/70

RUN NO. 13 FTI SEGMENTED REACTOR CASE 6 DATE 0/ 0/ 0

SPECIFIED VARIABLES

NUMBER OF BEDS= 3	FUEL AIR RATIO= .0746	BALLAST GAS DEMAND= 200.0 LBS/MIN
BED THICKNESS= 1.0 IN.	AVERAGE PRESSURE= 50.0PSIA	REACTION RATE CONSTANT= 194000.0/HR
RECYCLE RATE= .3750	AIR FLOW COEFFICIENTS	BED WEIGHTS

CALCULATED VARIABLES

OVERALL CONVERSION= .67

DUCT SIZE= 2.22 FT. SCALE UP FACTOR= 20902.7

	BED 1	BED 2	BED 3	TOTAL
AIR FLOW(LBS./HR)	.1638	.1922	.2256	.5816
AIR FLOW COEFFICIENT	.2816	.3305	.3879	1.0000
TOTAL FLOW(LBS./HR)	.5822	.7744	1.0000	2.3566
OXYGEN CONVERTED(LBS./HR)	.0257	.0299	.0348	.0904
CONVERSION COEFFICIENT	.2844	.3303	.3852	1.0000
OXYGEN CONCENTRATION IN	.1121	.1089	.1071	
OXYGEN CONCENTRATION OUT	.0679	.0704	.0722	
FRACTIONAL CONVERSION	.3938	.3539	.3252	
TEMP. RISE AT DESIGN COND.	396.13	782.50	706.65	
TEMP. RISE AT 100 PCT CONV.	1330.69	1174.10	1067.12	
SPACE VELOCITY/10**5 (1/HR)	3.8752	4.4410	4.9329	
BED WEIGHT (LBS.)	16.80	19.50	22.67	58.97
PRESSURE DROP (PSI)	.4629	.9492	1.8188	3.2309

8/31/76

RUN NO. 14 FTI SEGMENTED REACTOR CASE 4 DATE 0/ 0/ 0

SPECIFIED VARIABLES

NUMBER OF BEDS= 2 FUEL AIR RATIO= .0746 BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN. AVERAGE PRESSURE= 50.0PSIA REACTION RATE CONSTANT= 194000.0/HR
TEMP. RISE AT 100 PERCENT CONV.= 700.0 OVERALL CONVERSION= .85 TEMP. RISE AT DESIGN CONSTANT

CALCULATED VARIABLES

RECYCLE RATE= .7055
DUCT SIZE= 2.83 FT. SCALE UP FACTOR= 17806.7

	BED 1	BED 2	TOTAL
AIR FLOW(LBS./HR)	.1261	.1480	.2741
AIR FLOW COEFFICIENT	.4600	.5400	1.0000
TOTAL FLOW(LBS./HR)	.8520	1.0000	1.8520
OXYGEN CONVERTED(LBS./HR)	.0250	.0293	.0543
CONVERSION COEFFICIENT	.4600	.5400	1.0000
OXYGEN CONCENTRATION IN	.0614	.0618	
OXYGEN CONCENTRATION OUT	.0321	.0325	
FRACTIONAL CONVERSION	.4773	.4740	
TEMP. RISE AT DESIGN COND.	594.99	594.99	
TEMP. RISE AT 100 PCT CONV.	700.00	700.00	
SPACE VELOCITY/10**5 (1/HR)	2.9907	3.0196	
BED WEIGHT (LBS.)	27.14	31.55	58.69
PRESSURE DROP (PSI)	.3186	.4981	.8168

RUN NO. 15 FTI SEGMENTED REACTOR CASE 4 DATE 0/ 0/ 0

8/31/76

SPECIFIED VARIABLES

NUMBER OF BEDS= 4 FUEL AIR RATIO= .0746 BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN. AVERAGE PRESSURE= 50.0PSIA REACTION RATE CONSTANT= 19000.0/HR
TEMP. RISE AT 100 PERCENT CONV.= 700.0 OVERALL CONVERSION= .85 TEMP. RISE AT DESIGN CONSTANT

CALCULATED VARIABLES

RECYCLE RATE= .4517
DUCT SIZE= 1.86 FT.

SCALE UP FACTOR= 10317.2

	BED 1	BED 2	BED 3	BED 4	TOTAL
AIR FLOW(LBS./HR)	.0915	.1074	.1261	.1480	.4730
AIR FLOW COEFFICIENT	.1935	.2271	.2666	.3129	1.0000
TOTAL FLOW(LBS./HR)	.6185	.7259	.8520	1.0000	3.1964
OXYGEN CONVERTED(LBS./HR)	.0181	.0213	.0250	.0293	.0937
CONVERSION COEFFICIENT	.1935	.2271	.2666	.3129	1.0000
OXYGEN CONCENTRATION IN	.0603	.0609	.0614	.0613	
OXYGEN CONCENTRATION OUT	.0310	.0316	.0321	.0325	
FRACTIONAL CONVERSION	.4858	.4811	.4773	.4740	
TEMP. RISE AT DESIGN COND.	594.99	594.99	594.99	594.99	
TEMP. RISE AT 100 PCT CONV.	700.00	700.00	700.00	700.00	
SPACE VELOCITY/10**3 (1/HR)	2.9169	2.9568	2.9907	3.0196	
BED WEIGHT (LBS.)	11.70	13.55	15.72	18.28	59.26
PRESSURE DROP (PSI)	.3042	.4738	.7393	1.1559	2.6732

3/31/70

RUN NO. 16   FTI SEGMENTED REACTOR CASE 4   DATE 0/ 0/ 0

SPECIFIED VARIABLES

NUMBER OF BEDS= 3   FUEL AIR RATIO= .0746   BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN.   AVERAGE PRESSURE= 50.0PSIA   REACTION RATE CONSTANT= 194000.0/HR
TEMP. RISE AT 100 PERCENT CONV.= 700.0   OVERALL CONVERSION= .95   TEMP. RISE AT DESIGN CONSTANT

CALCULATED VARIABLES

RECYCLE RATE= .5900
DUCT SIZE= 3.27 FT.   SCALE UP FACTOR= 12817.8

	BED 1	BED 2	BED 3	TOTAL
AIR FLOW(LBS./HR)	.1074	.1261	.1480	.3815
AIR FLOW COEFFICIENT	.2816	.3305	.3879	1.0000
TOTAL FLOW(LBS./HR)	.7259	.8520	1.0000	2.5779
OXYGEN CONVERTED(LBS./HR)	.0238	.0279	.0328	.0844
CONVERSION COEFFICIENT	.2816	.3305	.3879	1.0000
OXYGEN CONCENTRATION IN	.0433	.0435	.0436	
OXYGEN CONCENTRATION OUT	.0105	.0107	.0108	
FRACTIONAL CONVERSION	.7566	.7538	.7513	
TEMP. RISE AT DESIGN COND.	664.99	664.99	664.99	
TEMP. RISE AT 100 PCT CONV.	700.00	700.00	700.00	
SPACE VELOCITY/10**5 (1/HR)	1.3727	1.3842	1.3940	
BED WEIGHT (LBS.)	36.26	42.21	49.19	127.66
PRESSURE DROP (PSI)	.0737	.1153	.1808	.3698

RUN NO. 17 FTI SEGMENTED REACTOR CASE 4 DATE 0/ 0/ 0

8/31/76

SPECIFIED VARIABLES

NUMBER OF BEDS= 3 FUEL AIR RATIO= .0746 BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN. AVERAGE PRESSURE= 50.0PSIA REACTION RATE CONSTANT= 194000.0/HR
TEMP. RISE AT 100 PERCENT CONV.= 700.0 OVERALL CONVERSION= .75 TEMP. RISE AT DESIGN CONSTANT

CALCULATED VARIABLES

RECYCLE RATE= .5900
DUCT SIZE= 1.73 FT. SCALE UP FACTOR= 12767.3

	BED 1	BED 2	BED 3	TOTAL
AIR FLOW(LBS./HR)	.1074	.1251	.1480	.3815
AIR FLOW COEFFICIENT	.2816	.3305	.3879	1.0000
TOTAL FLOW(LBS./HR)	.7259	.8520	1.0000	2.5779
OXYGEN CONVERTED(LBS./HR)	.0188	.0220	.0259	.0667
CONVERSION COEFFICIENT	.2816	.3305	.3879	1.0000
OXYGEN CONCENTRATION IN	.0783	.0794	.0801	
OXYGEN CONCENTRATION OUT	.0527	.0535	.0542	
FRACTIONAL CONVERSION	.3293	.3259	.3230	
TEMP. RISE AT DESIGN COND.	524.99	524.99	524.99	
TEMP. RISE AT 100 PCT CONV.	700.00	700.00	700.00	
SPACE VELOCITY/10**5 (1/HR)	4.8573	4.9200	4.9734	
BED WEIGHT (LBS.)	10.21	11.83	13.73	35.77
PRESSURE DROP (PSI)	.[illegible]398	1.2463	1.9462	3.9923

8/31/70

RUN NO. 18 FTI SEGMENTED REACTOR CASE 4 DATE 0/ 0/ 0

SPECIFIED VARIABLES

NUMBER OF BEDS= 3 FUEL AIR RATIO= .0746 BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN. AVERAGE PRESSURE= 50.0PSIA REACTION RATE CONSTANT= 194000.0/HR
TEMP. RISE AT 100 PERCENT CONV.= 700.0 OVERALL CONVERSION= .65 TEMP. RISE AT DESIGN CONSTANT

CALCULATED VARIABLES

RECYCLE RATE= .5900
DUCT SIZE= 1.41 FT. SCALE UP FACTOR= 12742.2

	BED 1	BED 2	BED 3	TOTAL
AIR FLOW(LBS./HR)	.1074	.1261	.1480	.3815
AIR FLOW COEFFICIENT	.2816	.3305	.3879	1.0000
TOTAL FLOW(LBS./HR)	.7259	.8520	1.0000	2.5779
OXYGEN CONVERTED(LBS./HR)	.0163	.0191	.0224	.0578
CONVERSION COEFFICIENT	.2816	.3305	.3879	1.0000
OXYGEN CONCENTRATION IN	.0962	.0973	.0983	
OXYGEN CONCENTRATION OUT	.0738	.0749	.0759	
FRACTIONAL CONVERSION	.2331	.2303	.2280	
TEMP. RISE AT DESIGN COND.	454.99	454.99	454.99	
TEMP. RISE AT 100 PCT CONV.	700.00	700.00	700.00	
SPACE VELOCITY/10**5 (1/HR)	7.3107	7.4112	7.4968	
BED WEIGHT (LBS.)	6.77	7.84	9.09	23.70
PRESSURE DROP (PSI)	1.7428	2.7137	4.2345	8.6910

8/31/70

RUN NO. 19 FTI SEGMENTED REACTOR CASE 6 DATE 0/ 0/ 0

SPECIFIED VARIABLES

NUMBER OF BEDS= 3 FUEL AIR RATIO= .0746 BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN. AVERAGE PRESSURE= 50.0PSIA REACTION RATE CONSTANT= 150000.0/HR
RECYCLE RATE= .5900 AIR FLOW COEFFICIENTS BED WEIGHTS

CALCULATED VARIABLES

OVERALL CONVERSION= .80
DUCT SIZE= 2.23 FT. SCALE UP FACTOR= 12779.5

	BED 1	BED 2	BED 3	TOTAL
AIR FLOW(LBS./HR)	.1074	.1261	.1480	.3815
AIR FLOW COEFFICIENT	.2816	.3305	.3879	1.0000
TOTAL FLOW(LBS./HR)	.7259	.8520	1.0000	2.5779
OXYGEN CONVERTED(LBS./HR)	.0201	.0236	.0277	.0713
CONVERSION COEFFICIENT	.2813	.3306	.3881	1.0000
OXYGEN CONCENTRATION IN	.0694	.0701	.0706	
OXYGEN CONCENTRATION OUT	.0418	.0424	.0429	
FRACTIONAL CONVERSION	.3982	.3948	.3919	
TEMP. RISE AT DESIGN COND.	560.86	561.49	561.73	
TEMP. RISE AT 100 PCT CONV.	700.09	700.05	700.03	
SPACE VELOCITY/10**5 (1/HR)	2.9542	2.9873	3.0159	
BED WEIGHT (LBS.)	16.80	19.50	22.67	58.97
PRESSURE DROP (PSI)	.3150	.4916	.7686	1.5753

5/31/70

RUN NO. 20 FTI SEGMENTED REACTOR CASE 4 DATE 0/ 0/ 0

SPECIFIED VARIABLES

NUMBER OF BEDS= 3 FUEL AIR RATIO= .0746 BALLAST GAS OF AND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN. AVERAGE PRESSURE= 50.0PSIA REACTION RATE CONSTANT= 150000.0/HR
TEMP. RISE AT 100 PERCENT CONV.= 700.0 OVERALL CONVERSION= .85 TEMP. RISE AT DESIGN CONSTANT

CALCULATED VARIABLES

RECYCLE RATE= .5900
DUCT SIZE= 2.53 FT. SCALE UP FACTOR= 12792.5

	BED 1	BED 2	BED 3	TOTAL
AIR FLOW(LBS./HR)	.1074	.1261	.1480	.3815
AIR FLOW COEFFICIENT	.2816	.3305	.3879	1.0000
TOTAL FLOW(LBS./HR)	.7259	.8520	1.0000	2.5779
OXYGEN CONVERTED(LBS./HR)	.0213	.0250	.0293	.0756
CONVERSION COEFFICIENT	.2816	.3305	.3879	1.0000
OXYGEN CONCENTRATION IN	.0609	.0614	.0618	
OXYGEN CONCENTRATION OUT	.0316	.0321	.0325	
FRACTIONAL CONVERSION	.4811	.4773	.4740	
TEMP. RISE AT DESIGN COND.	594.99	594.99	594.99	
TEMP. RISE AT 100 PCT CONV.	700.00	700.00	700.00	
SPACE VELOCITY/10**5 (1/HR)	2.2862	2.3124	2.3347	
BED WEIGHT (LBS.)	21.73	25.22	29.31	76.26
PRESSURE DROP (PSI)	.1938	.3025	.4729	.9693

RUN NO. 21   FTI SEGMENTED REACTOR CASE 4   DATE 9/29/70

SPECIFIED VARIABLES

NUMBER OF BEDS= 1   FUEL AIR RATIO= .0746   BALLAST GAS DEMAND= 60.0 LBS/MIN
BED THICKNESS= 1.5 IN.   AVERAGE PRESSURE= 50.0PSIA   REACTION RATE CONSTANT= 194000.0/HR
TEMP. RISE AT 100 PERCENT CONV.= 700.0   OVERALL CONVERSION= .85   TEMP. RISE AT DESIGN CONSTANT

CALCULATED VARIABLES

RECYCLE RATE= .8410
DUCT SIZE= 3.39 FT.   SCALE UP FACTOR= 32978.1

	BED 1	TOTAL
AIR FLOW(LBS./HR)	.1480	.1480
AIR FLOW COEFFICIENT	1.0000	1.0000
TOTAL FLOW(LBS./HR)	1.0000	1.0000
OXYGEN CONVERTED(LBS./HR)	.0293	.0293
CONVERSION COEFFICIENT	1.0000	1.0000
OXYGEN CONCENTRATION IN	.0618	
OXYGEN CONCENTRATION OUT	.0325	
FRACTIONAL CONVERSION	.4760	
TEMP. RISE AT DESIGN COND.	594.99	
TEMP. RISE AT 100 PCT CONV.	700.00	
SPACE VELOCITY/10**5 (1/HR)	3.0196	
BED WEIGHT (LBS.)	58.43	58.43
PRESSURE DROP (PSI)	1.0301	1.0301

RUN NO. 22 FTI SEGMENTED REACTOR CASE 3 DATE 9/29/70

SPECIFIED VARIABLES

NUMBER OF BEDS= 3 FUEL AIR RATIO= .0746 BALLAST GAS DEMAND= 8.0 LBS/MIN
BED THICKNESS= 1.0 IN. AVERAGE PRESSURE= 50.0PSIA REACTION RATE CONSTANT= 19000.0/HR
RECYCLE RATE= .9000 AIR FLOW COEFFICIENTS BED WEIGHTS

CALCULATED VARIABLES

OVERALL CONVERSION= 1.00
DUCT SIZE= 2.43 FT. SCALE UP FACTOR= 5260.0

	BED 1	BED 2	BED 3	TOTAL
AIR FLOW(LBS./HR)	.0931	.0000	.0000	.0931
AIR FLOW COEFFICIENT	1.0000	.0000	.0000	1.0000
TOTAL FLOW(LBS./HR)	1.0000	1.0000	1.0000	3.0000
OXYGEN CONVERTED(LBS./HR)	.0165	.0041	.0010	.0216
CONVERSION COEFFICIENT	.7603	.1915	.0482	1.0000
OXYGEN CONCENTRATION IN	.0220	.0055	.0014	
OXYGEN CONCENTRATION OUT	.0055	.0014	.0004	
FRACTIONAL CONVERSION	.7481	.7481	.7481	
TEMP. RISE AT DESIGN COND.	334.09	84.15	21.20	
TEMP. RISE AT 100 PCT CONV.	440.16	.00	.00	
SPACE VELOCITY/10**5 (1/HR)	1.4070	1.4070	1.4070	
BED WEIGHT (LBS.)	20.00	20.00	20.00	60.00
PRESSURE DROP (PSI)	.0858	.0924	.0941	.2723

RUN NO. 23 FIXED BED ... REACTOR CASE 4 DATE 10/ 2/70

SPECIFIED VARIABLES

NUMBER OF BEDS= 1 FUEL AIR RATIO= .0746 BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN. AVERAGE PRESSURE= 50.0PSIA REACTION RATE CONSTANT= 194000.0/HR
TEMP. RISE AT 100 PERCENT CONV.= 793.0 OVERALL CONVERSION= .75 TEMP. RISE AT DESIGN CONSTANT

CALCULATED VARIABLES

RECYCLE RATE= .8198
DUCT SIZE= 3.19 FT. SCALE UP FACTOR= 29053.2

	BED 1	TOTAL
AIR FLOW(LBS./HR)	.1277	.1277
AIR FLOW COEFFICIENT	1.0000	1.0000
TOTAL FLOW(LBS./HR)	1.0000	1.0000
OXYGE CONVERTED(LBS./HR)	.0293	.0293
CONVERSION COEFFICIENT	1.0000	1.0000
OXYGE. CONCENTRATION IN	.0838	
OXYGE. CONCENTRATION OUT	.0543	
FRACTIONAL CONVERSION	.3500	
TEMP. RISE AT DESIGN COND.	594.74	
TEMP. RISE AT 100 PCT CONV.	793.00	
SPACE VELOCITY/10**5 (1/HR)	4.4598	
BED WEIGHT (LBS.)	34.62	34.62
PRESSURE DROP (PSI)	.6757	.6757

RUN NO. 24   FTI SEGMENTED REACTOR CASE 4   DATE 10/ 2/70

SPECIFIED VARIABLES

NUMBER OF BEDS= 3   FUEL AIR RATIO= .0746   BALLAST GAS DEMAND= 80.0 LBS/MIN
BED THICKNESS= 1.0 IN.   AVERAGE PRESSURE= 50.0PSIA   REACTION RATE CONSTANT= 194000.0/HR
TEMP. RISE AT 100 PERCENT CONV.= 793.0   OVERALL CONVERSION= .75   TEMP. RISE AT DESIGN CONSTANT

CALCULATED VARIABLES

RECYCLE RATE= .5451
DUCT SIZE= 1.70 FT.   SCALE UP FACTOR= 11505.6

	BED 1	BED 2	BED 3	TOTAL
AIR FLOW(LBS./HR)	.1162	.1395	.1677	.4233
AIR FLOW COEFFICIENT	.2744	.3296	.3960	1.0000
TOTAL FLOW(LBS./HR)	.6528	.8323	1.0000	2.5251
OXYGEN CONVERTED(LBS./HR)	.0203	.0244	.0293	.0740
CONVERSION COEFFICIENT	.2744	.3296	.3960	1.0000
OXYGEN CONCENTRATION IN	.0817	.0827	.0835	
OXYGEN CONCENTRATION OUT	.0524	.0534	.0542	
FRACTIONAL CONVERSION	.3586	.3543	.3509	
TEMP. RISE AT DESIGN COND.	594.74	594.74	594.74	
TEMP. RISE AT 100 PCT CONV.	793.00	793.00	793.00	
SPACE VELOCITY/10**5 (1/HR)	4.3691	4.4350	4.4898	
BED WEIGHT (LBS.)	9.76	11.55	13.71	35.02
PRESSURE DROP (PSI)	.6425	1.0678	1.7795	3.4899

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Security Classification

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY AF Aero Propulsion Laboratory Wright-Patterson AFB, Ohio 45433

13. ABSTRACT

Fuel tank inerting requirements for two typical military aircraft have been established. With these requirements as a basis various inerting systems using a catalytic combustor have been considered and an optimum configuration has been selected for further study. A preliminary design has been completed on this configuration, including weights, general configuration, control functions and performance. The weight of the system is approximately 50% of a liquid nitrogen system designed to meet the same requirements. The moisture added to the fuel tanks is approximately the same as that added to the current fuel systems which do not have inerting systems. A program plan for the follow-on program which consists of building and testing a breadboard system of this configuration has been prepared.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
fuel tank inerting						
catalytic reactor						
catalyst testing						
air cycle machine						
maximum oxygen content						
scrubbing						
ullage						

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